AD NUMBER
ADB127562
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Administrative/Operational Use; SEP 1988. Other requests shall be referred to Arnold Engineering Development Center, Arnold AFB, TN.**
AUTHORITY
AEDC ltr 1 Aug 1989

AEDC-TR-88-27

C-3

Composite Material Tester

Kamran Majidzadeh, Behzad Vedaie and George J. Ilves
Resource International, Inc.
281 Enterprise Dr.
Columbus, Ohio 43229

September 1988

Final Report for Period August 7, 1987 – March 7, 1988

per AF letter, 1 Aug 89, signed by C.L. Garner/DOCS

~~Distribution authorized to U. S. Government agencies only; administrative/operational use–SBIR Phase I; September 1988. Other requests for this document shall be referred to Arnold Engineering Development Center/DOCS, Arnold Air Force Base, TN 37389-5000.~~

WARNING

~~This document contains technical data whose export is restricted by the Arms Export Control Act (Title 22, U.S.C., Sec 2751 et seq.) or The Export Administration Act of 1979, as amended. Title 50, U.S.C., App. 2401, et seq. Violations of these export laws are subject to severe criminal penalties. Disseminate in accordance with the provisions of AFR 80-34.~~

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE BASE, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

NOTICES

When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Technical Information Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

DESTRUCTION NOTICE

For classified documents, follow the procedures in DoD 5220.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX. For unclassified, limited documents, destroy by any method that will prevent disclosure or reconstruction of the document.

APPROVAL STATEMENT

This report has been reviewed and approved.

Robert G. Foster

ROBERT G. FOSTER, Major, CF
Facility Technology Division
Directorate of Technology
Deputy for Operations

Approved for publication:

FOR THE COMMANDER

Marion L. Laster

MARION L. LASTER
Technical Director
Directorate of Technology
Deputy for Operations

NOTICE TO ACCOMPANY THE DISSEMINATION OF EXPORT-CONTROLLED TECHNICAL DATA

1. Export of information contained herein, which includes, in some circumstances, release to foreign nationals within the United States, without first obtaining approval or license from the Department of State for items controlled by the International Traffic in Arms Regulations (ITAR), or the Department of Commerce for items controlled by the Export Administration Regulations (EAR), may constitute a violation of law.

2. Under 22 U.S.C. 2778 the penalty for unlawful export of items or information controlled under the ITAR is up to 2 years imprisonment, or a fine of $100,000, or both. Under 50 U.S.C., Appendix 2410, the penalty for unlawful export of items or information controlled under the EAR is a fine of up to $1,000,000, or five times the value of the exports, whichever is greater; or for an individual, imprisonment of up to 10 years, or a fine of up to $250,000, or both.

3. In accordance with your certification that establishes you as a "qualified U.S. contractor," unauthorized dissemination of this information is prohibited and may result in disqualification as a qualified U.S. contractor, and may be considered in determining your eligibility for future contracts with the Department of Defense.

4. The U.S. Government assumes no liability for direct patent infringement, or contributory patent infringement or misuse of technical data.

5. The U. S. Government does not warrant the adequacy, accuracy, currency, or completeness of the technical data.

6. The U.S. Government assumes no liability for loss, damage, or injury resulting from manufacture or use for any purpose of any product, article, system, or material involving reliance upon any or all technical data furnished in response to the request for technical data.

7. If the technical data furnished by the Government will be used for commercial manufacturing or other profit potential, a license for such use may be necessary. Any payments made in support of the request for data do not include or involve any license rights.

8. A copy of this notice shall be provided with any partial or complete reproduction of these data that are provided to qualified U.S. contractors.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited. ~~SEE REVERSE OF THIS PAGE~~ Per AF letter, 1 Aug 89 signed by C.L. Garner/Docs
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AEDC-TR-88-27	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Resource International, Inc. 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 281 Enterprise Drive Westerville, OH 43081	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Arnold Engineering Development Center 8b. OFFICE SYMBOL (If applicable) DO	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F40600-87-C0009
8c. ADDRESS (City, State, and ZIP Code) Air Force Systems Command Arnold Air Force Base, TN 37389-5000	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO: 65502F PROJECT NO.: TASK NO: WORK UNIT ACCESSION NO.:

11. TITLE (Include Security Classification)

Composit Material Tester

12. PERSONAL AUTHOR(S)

Majidzadeh, K., Vedaie, B., and Ilves, G. J., Resource International, Inc.

13a. TYPE OF REPORT	13b TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 8/7/87 TO 3/7/88	September 1988	81

16. SUPPLEMENTARY NOTATION

Available in Defense Technical Information Center (DTIC).

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
11	04	
09	02	

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

composite material, strain rate effects, dynamic properties, Hopkinson bar, high strain rate, carbon-carbon material

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes the investigation of the suitability of various dynamic testing devices to be used with carbon-carbon composites at strain rates greater than 10^4/sec. These investigations have resulted in the selection and preliminary design of split Hopkinson bars to be used for compression, tension, and shear testing of composite materials, particularly carbon-carbon composites. Sepcimen sizes have also been investigated, and bar dimensions have been selected based on minimum specimen requirements. The availability and suitability of various strain measuring and data storage/digitizing equipment have been explored, and an instrumentation package has been recommended.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL C. L. Garner	22b TELEPHONE (Include Area Code) (615) 454-7813 22c OFFICE SYMBOL DOCS

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

3. DISTRIBUTION/AVAILABILITY OF REPORT

Distribution authorized to U. S. Government agencies only; administrative/operational use--SBIR Phase I; September 1988. Other requests for this document shall be referred to Arnold Engineering Development Center/DOCS, Arnold Air Force Base, TN 37389-5000.

PREFACE

The work reported herein was conducted by Resource International Inc. under the Department of Defense Small Business Innovative Research Program (SBIR) Phase I. The monitoring agency was the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee. The Air Force Project Manager was Major Robert G. Foster, Canadian Forces. The report was submitted for publication August 20, 1988. The reproducibles used in the reproduction of this report were supplied by the authors.

Several Researchers participated in this study in various capacities. The authors wish particularly to acknowledge the contribution of Dr. R.L. Sierakowski and Dr. S. Chaturvedi of The Ohio State University who were the subcontractors on this project and contributed valuable suggestions and insight to problem solution. Special thanks is also due to Mr. Dave Powers who researched available materials and electronic equipment needed for the manufacture of a viable tester, to Mrs. Donna Roberts for production and typing of the manuscript, and to Mr. John Harding for producing the figures herein.

TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION................................	1
	A. BACKGROUND............................	1
	B. OBJECTIVES............................	1
	C. SCOPE OF RESEARCH.....................	2
	D. REPORT ORGANIZATION...................	3
II	LITERATURE REVIEW..........................	4
	A. GENERAL APPROACHES TO HIGH STRAIN RATE TESTING..............................	4
	1. Drop Forge Tests..................	4
	2. Charpy Hammer Tests...............	6
	3. The Split Hopkinson Bar Tests.....	6
	B. PREVIOUS EXPERIENCE WITH THE HOPKINSON BAR...................................	11
	1. Shear Tests.......................	11
	2. Tension Tests.....................	13
	3. Tension Specimens.................	13
	4. Frictional Effects................	17
	5. Inertial Effects..................	18
	C. SUMMARY...............................	18
III	CONSIDERATIONS OF TEST SETUP..............	20
	A. FACTORS INFLUENCING DESIGN............	20
	1. Specimen Material Characteristics.	20
	2. Specimen Size Limitations.........	21
	3. Failure Modes.....................	21
	4. Bar Properties....................	21
	5. Bar Dimensions....................	22
	6. Strain Gage Location..............	22
	B. INSTRUMENTATION.......................	22
	C. LAUNCHING DEVICE......................	24
IV	WAVE PROPAGATION THEORY..................	26
	A. THEORY OF LONGITUDINAL WAVE PROPAGATION	26
	B. WAVE PROPAGATION AT DISCONTINUITIES..	29
	C. ANALYSIS OF STRAINS...................	33

TABLE OF CONTENTS
(CONCLUDED)

Section	Title	Page
V	DESIGN OF HOPKINSON BARS	38
	A. HOPKINSON PRESSURE BAR DESIGN	38
	B. COMPOSITE MATERIAL	39
	C. DESIGN OF COMPRESSION TEST	40
	D. DESIGN OF SHEAR TEST	43
	E. DESIGN OF TENSION TEST	45
	1. Design of Pressure Bars	45
	2. Design of Threaded Connection	52
	F. STRESS DISTRIBUTION	56
	G. CALIBRATION	61
VI	APPLICATION	63
	A. ANALYSIS OF MEASUREMENTS	65
	B. LIMITATION OF THE TESTER	66
VII	CONCLUSION	68
	REFERENCES	71

LIST OF FIGURES

Figure	Title	Page
1.	Dynamic Test Regions	5
2.	Compressive Split Hopkinson Bar Schematic	7
3.	Tensile Split Hopkinson Bar Schematic	9
4.	A Method of Holding Tension Specimens	10
5.	Shear Test Configuration	12
6.	A Possible Configuration for Tension Test	14
7.	Striker Bar Tensile Wave Trap Device	15
8.	Dumbbell Specimen for Tensile Test	16
9.	Hat Tension Specimen	16
10.	Gas Gun for Propelling the Impact Bar	25
11.	Equilibrium of Infinitesimal Longitudinal Bar	27
12.	Wave Propagation at Interface	31
13.	Wave Propagation at Three Bars Arrangement	32
14.	The Compression and Shear Hopkinson Bar and Its Lagrange Diagram	44
15.	Shear Specimen	46
16.	Possible Failure Modes In Interlaminar Shears	47
17.	Tension Specimen and Its Mounting	49
18.	Lagrange Diagram for Tension Tests	50
19.	Thread Type Profiles	55
20.	American Standard Unified Thread	57
21.	Threaded Specimen Holder Connection	59

LIST OF TABLES

Table	Title	Page
1.	Effect of Area Mismatch on Equilibrium Reflection	34
2.	Hopkinson Pressure Bars and Specimen Dimension	53
3.	Variation of Pitch Size on Shear Area	58
4.	Stress Concentration Factor	61

SECTION I

INTRODUCTION

A. BACKGROUND

Composite materials are increasingly being used for a variety of applications. For a number of reasons this increased use has raised serious concerns about the composite materials' reliability. First, they have an inherent statistical variability in their strength properties. Second, because these materials are heterogeneous, they exhibit complex modes of failure which are significantly different from those observed in metals. Third, they contain macroscopic flaws and cracks introduced during their manufacture as well as during service. Furthermore, these materials are often used in applications where they experience high rates of stress and strain. Therefore, the problems associated with the measurement of their strengths and stress-strain properties under static as well as high strain rate dynamic conditions are of major concern.

Of particular interest is the measurement of the composite materials' strengths under high strain rate loading conditions since there is some evidence to indicate that the ultimate strengths might be strain-rate dependent (Reference 1). The graphitic and carbon composite materials are known to behave as anisotropic materials containing three mutually orthogonal material symmetry axes because of their method of manufacture and fiber orientation. Therefore, up to nine elastic constants and six ultimate strength values may need to be determined before a successful design with these types of materials is possible.

B. OBJECTIVES

The primary objectives of this research project are:

1. To develop a concept in testing methodology that can lead to a practical testing device for ultimate tensile strengths (along three orthogonal material axes) and three ultimate shear strengths along the principal material planes at strain rates up to 10^4/min.

2. The testing device should have the following capabilities.

   a. To obtain stress-strain curves under tensile and compressive loading along each orthogonal symmetry axis.

   b. To perform tests at strain rates up to 10^4 in/in/min.

c. To perform a similar range of tests for shear strengths along three material symmetry planes.

d. Should require use of minimum material to obtain six principal strengths.

e. Should not introduce off-axis loading during testing.

It is important to realize that, due to the anisotropic nature of composite materials, all the strength parameters may be different and most probably will vary with the loading rate as well. Furthermore, appreciable errors in the principal strength values could occur if any off-axis loading is present, due to coupling phenomena observed in anisotropic materials. Also, strength values may be affected because of changes in failure modes. It is therefore important that these issues should be addressed in developing the concepts for a tester.

C. SCOPE OF RESEARCH

In order to achieve the objectives described in the previous section, the project has been divided into three primary tasks:

- Review of literature dealing with high strain rate testing.
- Modify/adapt existing concepts to the testing of carbon-carbon and graphite-graphite composites.
- Select specimen types and holding devices.

A thorough review of literature was undertaken to review available methods for high strain rate testing. This review resulted in identifying the split Hopkinson bar as the most feasible approach to be used for the required testing of composites. The Hopkinson bar has been used successfully to test metals and some composite materials, although it has not been used with the carbon-carbon and graphite-graphite composites of interest in this project. The Hopkinson bar will require some modification, as will be described in subsequent sections, to be suitable for use with the composite specimens, but the authors have every confidence that the proposed designs will meet the testing requirements.

Specimen dimensions and mounting methods have also been reviewed, and proposed designs are presented later in this report. The primary consideration in this regard has been specimen size in order to minimize the amount of material required and still retain a sufficient number of fiber bundles to make results meaningful.

D. REPORT ORGANIZATION

This report is divided into seven chapters as follows:

SECTION I. INTRODUCTION

SECTION II. LITERATURE REVIEW

SECTION III. CONSIDERATIONS OF TEST SETUP

SECTION IV. WAVE PROPAGATION THEORY

SECTION V. DESIGN OF HOPKINSON BARS

SECTION VI. APPLICATION

SECTION VII. CONCLUSIONS

The problem statement and project objective are described in Section I along with the report organization and a section describing project scope and research approach. Section II is devoted to literature review of high strain-rate testing methods, particularly as they apply to testing of composite materials. The issues and factors that need to be considered in testing setup design are described in Section III, along with a general consideration of equipment and instrumentation needs. The wave propagation theory required to evaluate test results from the split Hopkinson bar is explored in Section IV and the theory is applied to the bar designs in Section V. The testing configuration and specimen dimensions are similar in compression and shear, but the tension test setup is quite different and raises various issues; these are also discussed in Section V. Section VI contains a description of the application of the proposed testing method to determining the desired strength parameters of the composite materials, and a summary and the conclusions of this study are presented in Section VII.

SECTION II

LITERATURE REVIEW

A. GENERAL APPROACHES TO HIGH STRAIN RATE TESTING

Figure 1 shows the methods available for stress-strain testing and the approximate strain rate achievable by each method (Reference 2). The required strain rate of 10^4/min (1.7 x 10^2/sec.) is about an order of magnitude higher than can be achieved with mechanical or pneumatic/hydraulic testing machines and is on the raw edge of possibility using mechanical resonance machines. The disadvantage of the latter, however, is that relatively large specimens are required. Since, in general, only scraps are available from which to machine test specimens, sample size becomes of significant, if not of paramount, interest.

Two roughly similar test methods that have been used to achieve strain rates on the order of 10^2/sec. are the drop forge and the Charpy hammer tests. Another approach is the split Hopkinson bar where strain rates up to 10^4/sec. have been achieved. These methods will be described in the following sections.

1. Drop Forge Tests

The drop forge is a mechanical device that can be used to induce compressive strains in specimens at strain rates of 10^2/sec. or even higher. In this test a loading tup is raised to a predetermined height above the specimen and dropped. The falling tup is guided along rails to ensure axial alignment. If the tup energy is in excess of that required to deform the specimen, approximately constant velocity of deformation occurs; i.e., approximately constant strain rate is experienced by the test specimen. Thus, if the loading time is known, the specimen strain is easily obtained from tup velocity measurements. Force measurements, however, are more difficult, particularly at higher strain rates where wave propagation effects become more troublesome.

Holzer developed a setup in 1978 using piezoelectric load cells for force measurements and a fiber optics transducer for displacement measurements (Reference 3). The actual force information is obtained by a fast Fourier transform of the load cell signals which are then corrected for dynamic characteristics of the load cell in the frequency domain. This procedure was used by Holzer and Brown to measure the compressive stress-strain response of two steels at strain rates up to 10^3/sec. (Reference 4).

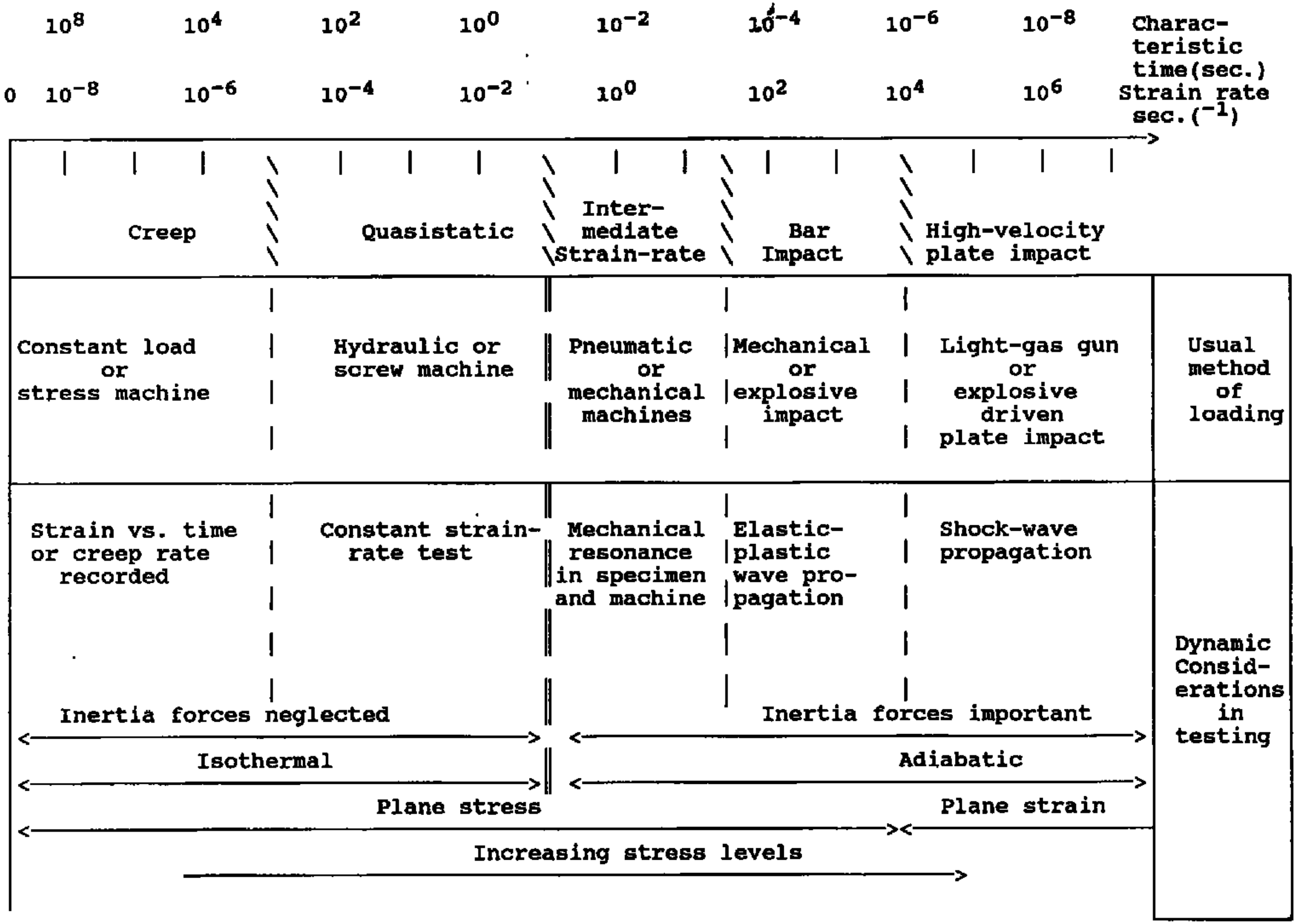


Figure 1. Dynamic Test Regions.

The advantages of this method are that the tup velocity and total energy are easily controlled and determined; however, force measurements are far from simple. Also, it is very difficult to devise a setup that allows testing under tensile strain. Therefore, this method is dropped from further consideration.

2. Charpy Hammer Tests

The Charpy test was developed in 1916; it involves the determination of the total energy-to-failure of a notched beam in three-point loading, although unnotched beams have also been used. The loading is applied by a tup of an impact pendulum at strain rates on the order of 100/sec. The primary purpose of the test is to screen materials and to compare energy-to-failure of similar materials under impact loading. Since only total energy is generally measured, the test cannot be used in determination of quantitative failure criteria for materials.

To overcome this problem, an instrumented version of the Charpy test has recently been developed with which the actual load-displacement history of a specimen can be obtained (Reference 5). The specimen loading is determined through strain gages placed directly on the tup and displacement is obtained from initial velocity and velocity decrease using energy considerations.

As in the drop forge test, inertial and wave propagation effects limit the strain rates that can be achieved in practice; as stated before, the practical limit is in the vicinity of 100/sec., which is somewhat lower than desirable. Also, although the geometry is such as to produce 3-point bending, two failure modes are possible. For isotropic materials the loading will lead to tensile failure at the outermost fibers. For anisotropic materials such as composites, however, the specimen may fail in interlaminar shear instead of in tension. Therefore, this method is also eliminated from consideration.

3. The Split Hopkinson Bar Tests

The split Hopkinson pressure bar, also known as the Kolsky apparatus, was developed by Kolsky in 1948 (Reference 6). The compressive pressure bar and its Lagrange diagram are shown schematically in Figure 2. (The setup for shear tests is very similar, as will be described in Section V.) It consists of a striker bar, an incident bar and a transmitter bar, with the specimen mounted between the incident and transmitter bars. As the striker bar, usually fired from a gas gun, impacts on the incident bar, it sets up a compressive stress wave that travels to the right in the incident bar and to the left in the striker bar. When this stress wave meets the interface between the incident bar and the specimen, some of this wave is reflected from this discontinuity because of the acoustic impedance

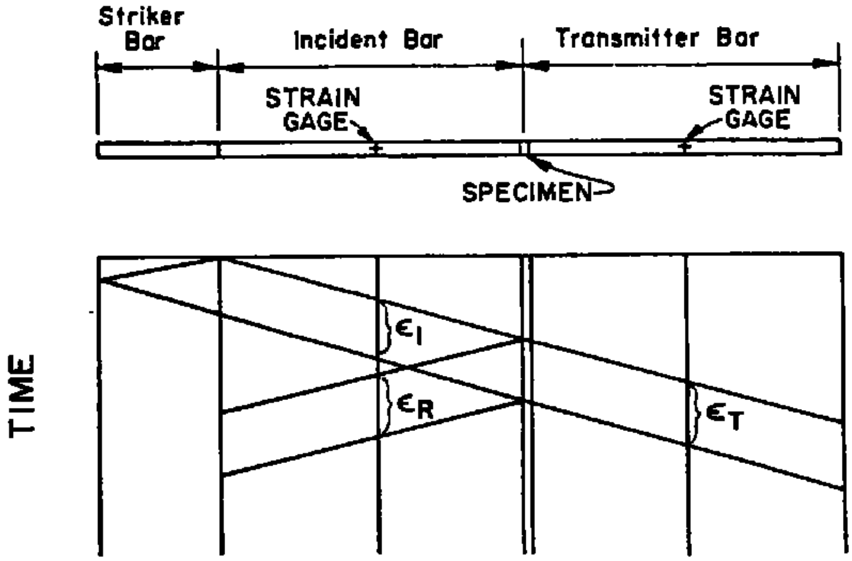


Figure 2. Compressive Split Hopkinson Bar Schematic.

mismatch while the rest is transmitted through the specimen to the transmitter bar. Of course, another reflection occurs at the interface between the specimen and the transmitter bar; this reflection sets up the steady-state stress condition in the specimen, as will be explained in a later section.

As indicated in the Lagrange diagram (Figure 2), the compressive stress wave also travels to the left in the striker bar and is reflected from the left end as a tension wave which is transmitted to the incident bar when this wave reaches the striker-incident bar interface. Essentially no reflection takes place at this interface because there is very little acoustical impedance mismatch at this junction. However, the test is terminated at this point because the tensile wave now reduces the stress in the specimen. It is seen that the test duration is twice the time required for the stress wave to travel through the striker bar.

The stress analysis in the bar is based on the assumption that as long as the bar remains elastic, the displacements at the end are propagated uniformly down the bar at elastic-wave velocity. Thus, a strain gage on the bar provides the force-time history at the end of the bar, but with some delay. The location of strain gages is discussed in more detail in Section V.

The tension Hopkinson bar is shown schematically in Figure 3, with the specimen mounting depicted in Figure 4. The timing sequence of this test is shown in the Lagrange diagram in Figure 3. When the striker bar impacts bar #1, it sets up a compression wave that travels to the right through bar #1 and to the left through the striker bar. The compression wave is transmitted to bar #2 through the split collar around the specimen (shown in Figure 4). The split collar must be somewhat longer than the gap between the incident and the transmitter bars in order to ensure good contact between the collar and the bars and thus to minimize the intensity of the wave reflected from this discontinuity. The compression wave continues to travel to the right through bar #2 and is reflected as a tension wave at the free end of bar #2. As this tension wave reaches the split collar, it cannot be transmitted through this collar since there is only a slight precompression between the collar and the bars and it therefore travels through the specimen, with some of it reflected from the specimen-transmitter bar interface. As in the compression test case, reflections of the tensile wave also occur at the bar-specimen interfaces due to the impedance mismatch at these locations; these reflections set up a steady-state stress condition in the specimen. Also, just as in the compression test, the compressive stress wave, generated as a result of the striker bar impact, travels to the left through the striker bar and is reflected from the free end as a secondary tension wave. When this secondary wave reaches the split collar, it unloads the collar to its original small precompression - it is

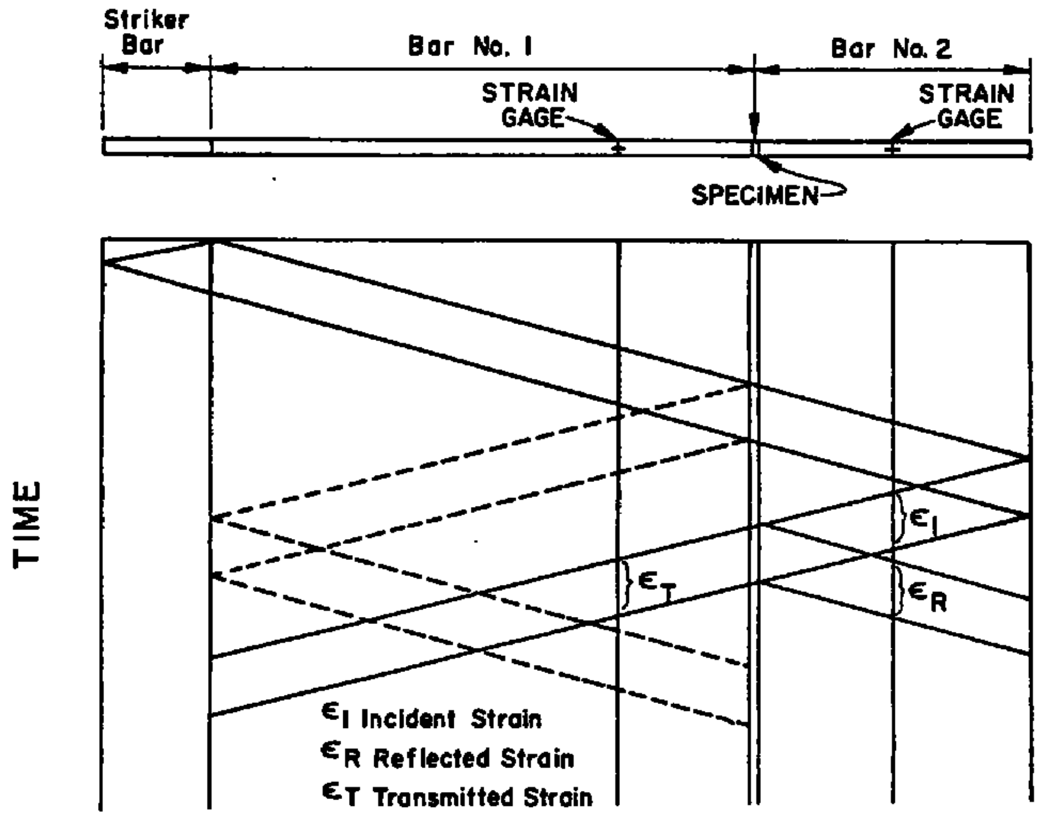


Figure 3. Tensile Split Hopkinson Bar Schematic.

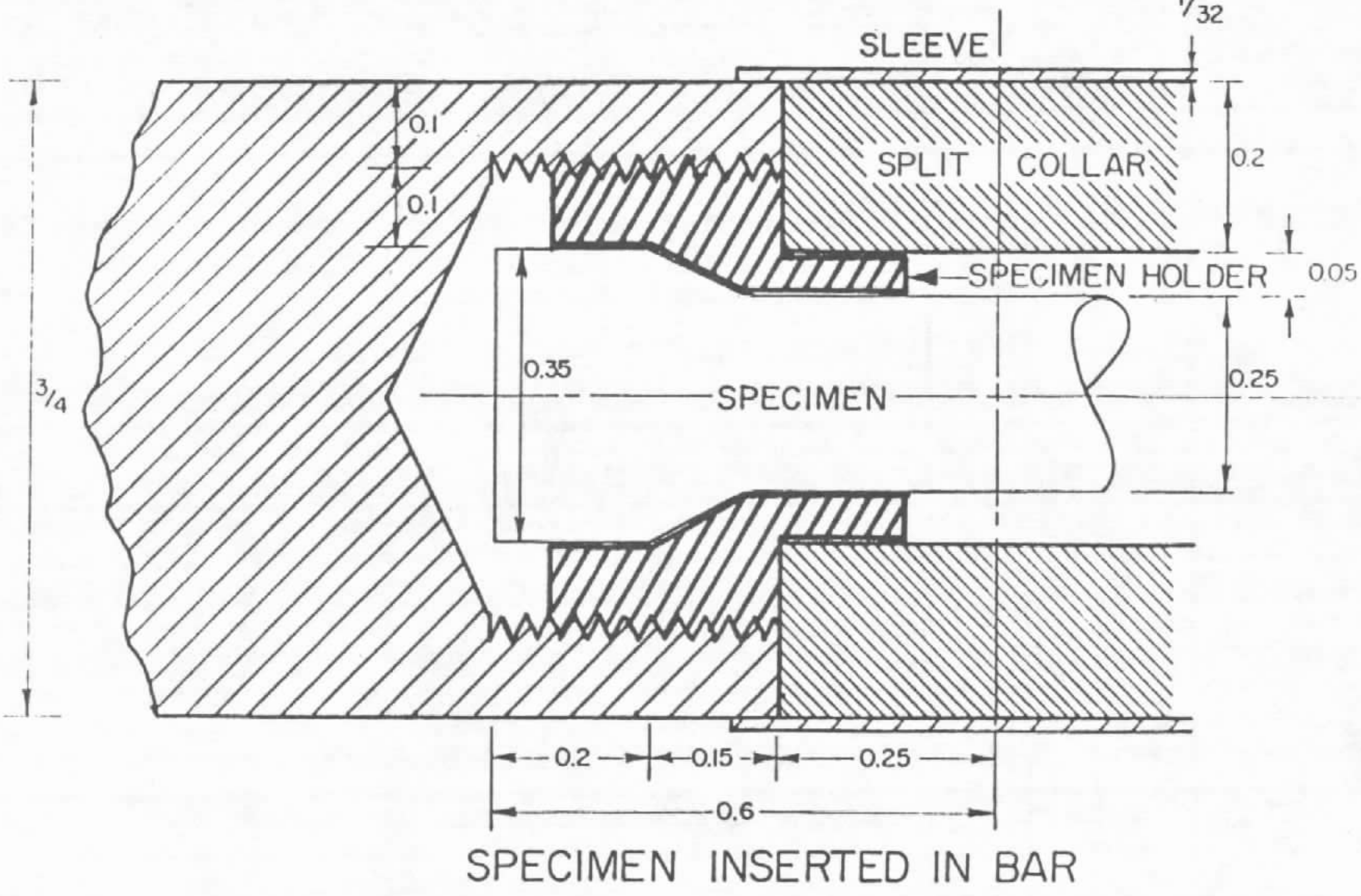


Figure 4. A Method of Holding Tension Specimens.

important that this event should occur before the original wave, now reflected from the end of bar #2 as a tension wave, reaches the specimen. This requirement restricts the striker bar to a maximum length, as will be shown in Section V.

The secondary (tension wave) travels through the split collar to the end of bar #2 at which point it is reflected as a compression wave. When this compression wave reaches the specimen, the specimen is unloaded and the test is terminated. Therefore, the length of the striker bar must be long enough to permit equilibrium to be reached in the specimen. Thus, both minimum and maximum lengths for the striker bar can be established, as will be shown later.

B. PREVIOUS EXPERIENCE WITH THE HOPKINSON BAR

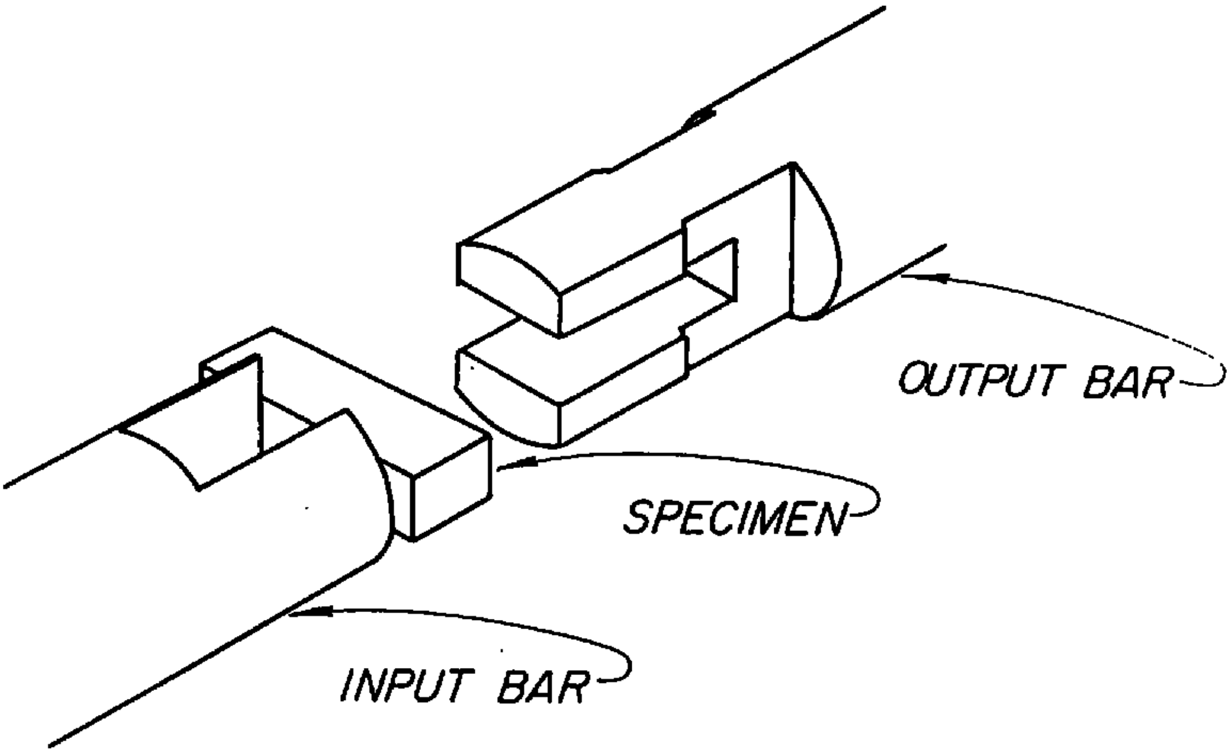
Since its inception in 1948, the split Hopkinson bar has primarily been used, both in the United States and elsewhere in the world, to conduct high strain rate testing of metals, although some testing of composites has been reported (References 1,6-17). The experience with composites has been mostly with fiber-epoxy or woven polyester and epoxy based materials, but some work has been done with metal composites as well (References 15,13,14,1). Some work has also been done with graphite fiber-epoxy laminates; however, no published information is available concerning carbon-carbon or graphite-graphite composites (Reference 15).

The Hopkinson bar was developed to perform compression tests, but several modifications have been proposed for using this apparatus in tension and shear tests (References 1,10,11,15,17). Several investigators have also used modifications of this apparatus to perform fracture toughness tests (References 12,17). Of primary interest to this study are the modifications required to convert the apparatus to tension and shear testing.

1. Shear Tests

Werner and Dharan modified the ends of the Hopkinson bar as shown in Figure 5 to conduct interlaminar and transverse shear tests on graphite fiber-reinforced epoxy specimens (Reference 15). Since the rest of the bar geometry is identical to the compression tests, the signal timing and bar length restrictions described earlier also apply to this test.

Werner and Dharan were able to achieve shear strain rates of up to 16,000/sec. at strain levels up to 40 percent, but they had significant scatter in their data (Reference 15). Some of this scatter is expected, particularly in the interlaminar shear tests where several failure modes are possible, depending on fiber bundle spacing and their location with respect to the



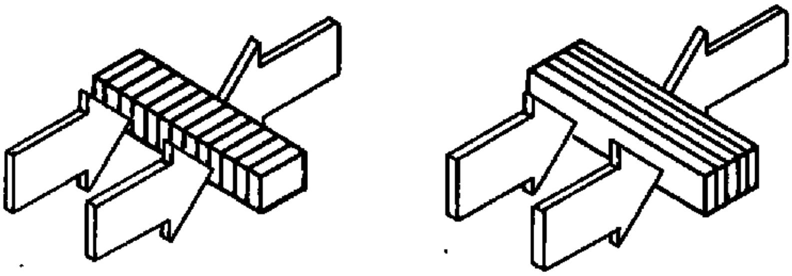


Figure 5. Shear Test Configuration.

anvils. In this respect it is important to conduct many tests and to select the lowest, rather than average, shear strength values and to inspect the specimens to determine the failure mode. The lowest values should be selected since higher values most probably represent non-critical failure modes; this can be determined from careful inspection of the failed specimens.

2. Tension Tests

Two methods have been proposed for using the Hopkinson bar in tension tests: the setup shown in Figure 3 (described earlier) and the configuration shown in Figure 6 (References 1,10). In the latter case a compressive stress wave is induced in the (outside) transmitter bars as the striker bar (ram) impacts on these bars. This compression wave is reflected from the right (free) end as a tension wave which now travels to the left in both the input and the transmitter bars. From here on, the timing is identical to that in the compression test, except that a tension wave instead of a compression wave travels through the bars and the specimen.

The advantage of the configuration in Figure 6 is that the primary wave sets up tension in the specimen so that a split collar is not needed. Furthermore, the secondary wave (from the left end of the striker bar) can easily be captured and prevented from coming back into the picture, thereby removing the restriction on striker bar length. The wave trap proposed by the authors is shown in Figure 7. The threaded tension rod holds the striker bar together during compression, but when the tension wave (reflected from the left end of the striker bar) arrives at the tension rod, this rod breaks, thereby severing the connection between the two halves of the striker bar and preventing the tension wave from being transmitted to the transmitter bars.

The disadvantage of this setup, however, is its complexity and the difficulty in achieving and maintaining alignment of the specimen and bars. Therefore, this concept will be abandoned and the configuration presented in Figure 3 will be adapted for use.

3. Tension Specimens

Tension specimens are generally dumbbell shaped with screw threads on each end for mounting. Such an arrangement has been used successfully by Nicholas and by Ross with metal alloy specimens (References 11,17). However, threaded specimens are difficult to implement when using composites, both because the threads are difficult to machine to close tolerances and because shear stresses in the threads can become significant for specific fiber orientations. Ross, et al. have also used the specimen mounting shown in Figure 4 (Reference 1). In fact, they compared test results of metal specimens obtained using both threaded samples and the mounting method shown in Figure 8 and concluded

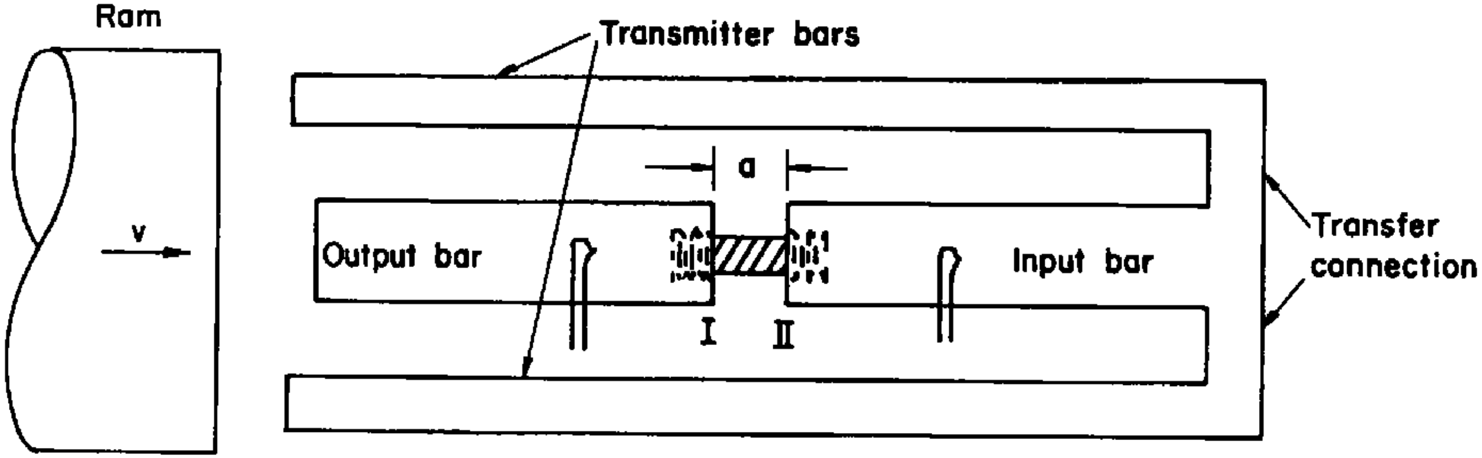


Figure 6. A Possible Configuration for Tension Test.

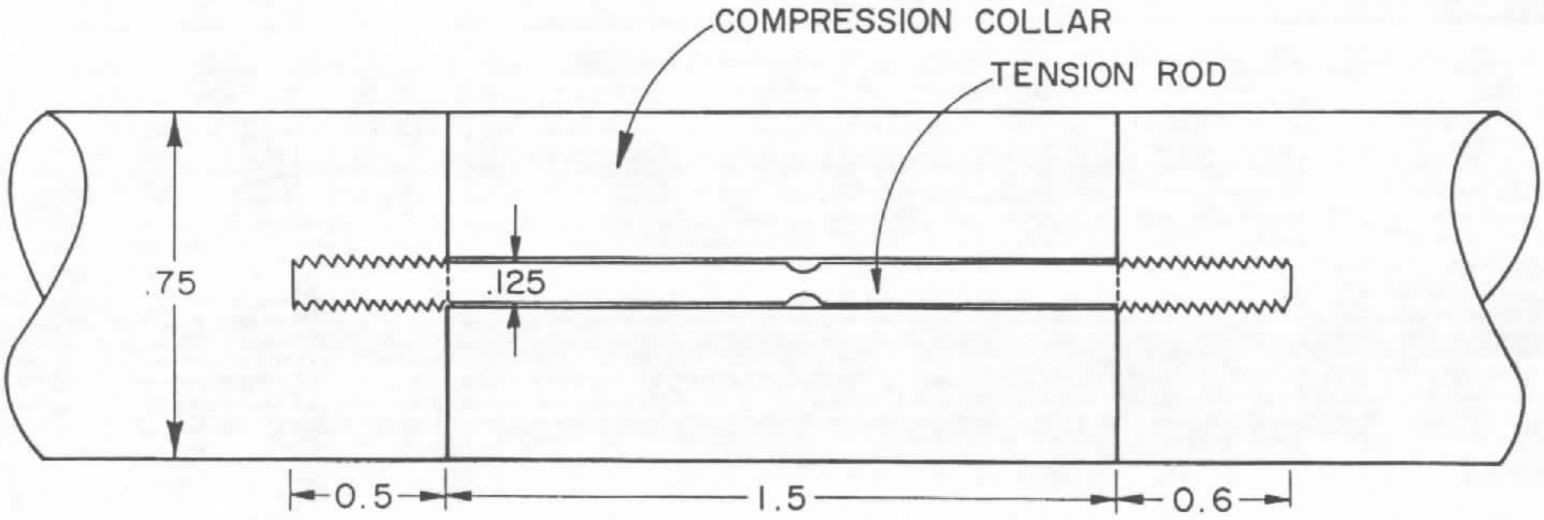


Figure 7. Striker Bar Tensile Wave Trap Device.

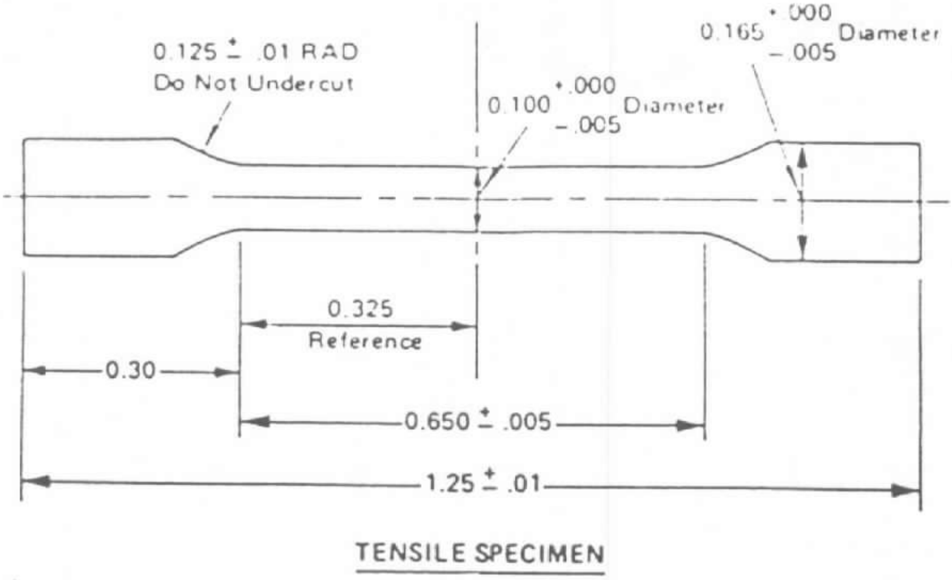


Figure 8. Dumbbell Specimen for Tensile Test.

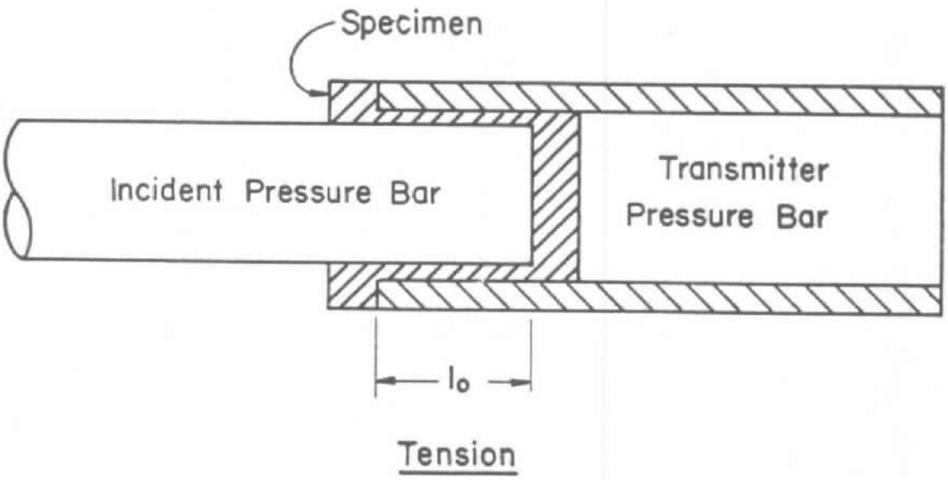


Figure 9. Hat Tension Specimen.

that the results are essentially the same (Reference 1). A slight modification of this method is proposed for use in this study. The modification is necessary because the composite specimen has to be considerably larger in diameter than a metal specimen in order to have enough fiber bundles in the cross section that nonsymmetric fiber bundle distribution will not result in significant off-axis loading.

Hat-shaped specimens have also been used in testing metal specimens in tension in a geometry shown in Figure 9 (Reference 17). While this method has been used successfully with homogeneous materials, it would be very difficult to machine samples out of composite materials without introducing nonsymmetric loading conditions due to nonsymmetric fiber bundle distribution within the specimens. Therefore, this sample geometry has been eliminated from consideration.

4. <u>Frictional Effects</u>

Davies and Hunter have shown that for compression tests the frictional forces at the specimen-bar interfaces can result in erroneous stress-strain relationship (Reference 8). Their analysis shows that the frictional effects are negligible if the specimen dimensions are selected such that

$$2 \mu a/3h < 1 \tag{1}$$

where a and h are the specimen radius and length, respectively, and μ is the coefficient of friction which, for lubricated ends, is on the order of 0.02 to 0.06. This leads to the requirement that the minimum value of h be at least on the same order as a.

Lindholm conducted tests on a series of aluminum specimens with diameter from 0.4 to 0.6 inch (10.2 to 15.2 mm) and length from 0.15 to 0.75 inch (3.8 to 19.1 mm), resulting in a/h ratios from 0.25 to 2.5 (Reference 7). His results show that the frictional effect is negligible for strains greater than about 6 percent and that at strain rates below this value the true stress increases somewhat as a/h decreases; the effect is on the order of 15 percent over the a/h ratios investigated at 2 percent strain level (Reference 7). The specimens in this test were lubricated using molybdenum disulfide lubricant.

Maiden and Green also investigated frictional effects using 3/8 inch (9.5 mm) diameter aluminum specimens with lengths of 1/2, 1/8, 1/16, 1/32, 1/64 and 1/128 inch (12.7, 3.2, 1.6, 0.8, 0.4, and 0.2 mm) (Reference 9). They found that repeatable measurements were obtained with specimens greater than 1/8 inch (3.2 mm) long, but that for tests with shorter specimens, the results varied greatly (Reference 9).

5. Inertial Effects

Two inertial effects have to be considered in high strain rate tests: axial and radial. The axial inertial effect rises due to finite specimen length and results in a non-uniform stress and strain along the specimen. The radial effect was first investigated by Kolsky; he showed that the actual stress required to produce a deformation in a specimen is less than measured because some of this stress was used in producing radial kinetic energy in the specimen (Reference 6). Davies and Hunter have conducted a detailed analysis of inertial effects using kinetic energy considerations and have shown that the radial and axial inertial effects are to some extent compensating and will compensate exactly if the specimen dimensions are such that

$$a/h = 1/\ (\nu\ \sqrt{3}) \tag{2}$$

where ν is the specimen's effective Poission's ratio and h and a are the specimen height and radius, respectively (Reference 8). Harden and Green conducted some experiments with specimens where the ratio of the radial to axial stress correction terms was about 0.1; even for this case the inertial effects were negligible (Reference 9). It therefore appears that if specimen dimensions are chosen such that a/h is about 1, both inertial and frictional effects can be reduced to negligible proportions.

C. SUMMARY

A review of literature was undertaken to identify methods that could be used for high strain rate testing of graphite-graphite and carbon-carbon composite and to identify what problems could be expected. The results of this investigation show that the Split Hopkinson Bar could be used for testing the composite in both tension and compression as well as shear, but the apparatus would have to be tailored for each test.

The literature review also indicated that inertial effects could be expected at high strain rates, but that these could be minimized with proper specimen dimension selection, as could frictional effects. Experiments conducted by several investigators show that if the specimen diameter is about twice its height, both frictional and inertial effects can be kept to negligible levels in compression testing.

Specimen type and mounting were also investigated. The specimen dimensions for compression testing are dictated by inertial and frictional considerations as indicated above, and specimen size selection for shear testing is primarily governed by the fiber bundle spacing. The tension specimens present more of a challenge, however, since threaded specimens, commonly used with metals and other isotropic materials, are not suitable for use for laminate and composite materials. A slight modification of the specimen design and mounting shown in Figure 4 are proposed for use in this study. This will be discussed further in Section V.

SECTION III

CONSIDERATIONS OF TEST SETUP

A. FACTORS INFLUENCING DESIGN

The major factors that influence the design of the Hopkinson bar setup were covered under the literature review in the previous chapter. There are, however, several other factors that have to be considered in experiment design. These include:

- Specimen material characteristic
- Specimen dimensions and size limitations
- Failure modes
- Bar material properties
- Bar dimensions
- Strain gage location

These will be described below.

1. Specimen Material Characteristics

The material properties of the specimens greatly influence the design of the Hopkinson apparatus. First, the fiber bundle spacing determines the minimum specimen dimensions that can be used; i.e., it is necessary that the specimen contain enough fiber bundles so that a nonsymmetric fiber distribution will not cause significant off-axis effects. Since the fiber bundle spacing of the composites is on the order of 0.05 in. (1.3 mm), the minimum specimen diameter for tension tests is 0.33 in. (8.4 mm); the specimen dimensions will be described in more detail in Section V. Also of interest is the fiber orientation. The method of manufacture of the graphitic specimens results in a material with three orthogonal axes of symmetry; therefore, specimen properties will have to be determined along each of these axes.

Second, the specimen ultimate strength values are of interest since these dictate the bar diameter and yield strength required in order that the bars remain elastic during the test, although the choice of bar diameter is also dependent on minimizing the time required to achieve equilibrium stress conditions in the specimen, as will be explained later.

The material Poisson's ratio is also important. It was shown previously that the inertial effects in compression tests could be reduced or even eliminated if the specimen height to diameter ratio was chosen properly and that this ratio depended on the specimen Poisson's ratio. Published data regarding the Poisson's ratio of carbon-carbon and graphite-graphite composites is lacking in literature, nor is it known if Poisson's ratio is strain rate dependent. The investigation of the composites'

Poisson's ratio is one of the first tasks to be conducted during Phase II.

Perhaps the most critical specimen material property is the wave velocity within the specimen which is proportional to the specimen effective modulus and mass density. This property determines the length of time that is required for the stress wave to travel through the specimen and, hence, the time required for the specimen to achieve an equilibrium stress state, as will be shown in Section IV. It is not known precisely what the wave velocity in the composite specimens is; therefore, one task of Phase II research is to determine this wave velocity before final Hopkinson bar dimensions can be fixed.

2. Specimen Size Limitations

It was indicated in the discussion in Section II that some electro-mechanical devices (such as resonance machines) are capable of reaching the strain rates required for this study. However, these machines require specimens that are relatively large (on the order of 1/2 inch (13 mm) diameter and 2 to 3 inches (51 to 76 mm) long). Specimens of this size would be very difficult to obtain without wasting precious material. Therefore, every attempt is being made to keep specimen dimensions small enough so that the specimens could be manufactured from scrap material. This requirement of small sample size is one of the factors in selecting the Hopkinson bar apparatus for specimen testing.

Of course, as alluded to above, minimum dimensions must be maintained in order that the measurements be representative of the composite and so that nonsymmetric fiber bundle distribution within the specimen would not introduce significant off-axis effects.

3. Failure Modes

While failure modes are factors in all tests, their importance increases in interlaminar shear. Since the fiber fundle spacing is not entirely uniform, it is impossible to prepare specimens such that shear failure can be guaranteed to take place in the matrix or along the fiber bundle planes or any other specific location. Therefore, as discussed previously, it is important to conduct several tests and inspect the specimens' failure mode before critical shear strength can be determined.

4. Bar Properties

As will be discussed in Section IV, the analysis of the strain gage data will yield the condition of stress at the ends of the bar only if the bar remains elastic during the test. It is, therefore, necessary that the bar yield strength be higher than that of the material being tested. Particular attention is required in areas of high stress concentration such as the bar faces. Another critical area is the thread design used in mounting of the tension specimens (Figure 4). Special thread design (Modified American Standard) is proposed to minimize shear stresses and the effects of stress concentration and hardened 420 stainless steel has been selected for bar material. This material has a static yield strength in excess of 195,000 psi (1.3 GPa) and should be adequate not only for testing of composite specimens, but aluminum and some other metal specimens as well.

5. Bar Dimensions

The major effort in designing the Hopkinson bar apparatus is in determining the bar diameter and lengths required for the specific tests. As will be discussed in Section IV, the bar diameter is not only dependent on specimen dimensions, it also influences the length of time required to achieve an equilibrium stress in the specimen in that the numbers of reflections within the specimen to reach equilibrium is a function of the ratio of the bar and specimen cross-sectional areas. The bar lengths are then chosen such that the total time available for the test (as determined by the time between the primary and secondary waves described in Section II) is greater than the time required to reach equilibrium within the specimen. The details of the bar design are discussed in Section V.

6. Strain Gage Location

As has been indicated in previous discussion, the condition (stress, displacement) of the ends of the bars can be determined by analyzing the strain in the bars provided that the strain gages are located appropriately; i.e., it is necessary that the strain gages record the information representative of conditions during specimen loading. This means that they must be located at specific distances from the specimen ends. The exact location for strain gage placement is discussed in Section V for each test type.

B. INSTRUMENTATION

Instrumentation is required in two areas. First, the impact bar velocity needs to be measured just before impact. The proven method for this purpose is to use a timer along with magnetic pickups that sense the passage of two bands on the striker bar. As each band passes the magnetic pickup, a voltage pulse will be generated in the pickup which can be used to turn the timer on and off. The velocity can then be calculated based on the distance between the bands and the time measured by the timer.

It is proposed to use a Textronix DC5009 programmable timer/counter with a 100 ns time resolution. Even at 100 ft./sec. (30.5 m/sec.) striker bar velocities, this will be more than adequate for better than 0.1 percent measurements. This timer also has interfacing with microcomputers to transmit time data to the microcomputer for processing.

Second, instrumentation is required to process the signals received from the two strain gages and to digitize this data for further processing in a microcomputer. The conventional technique for this would be to use strain gage amplifiers for signal amplification/conditioning, followed by a digitizer. However, strain amplifiers with band widths greater than about 150 kHz (3dB) are not available. Since the expected rise time of the strain signals is on the order of 2 to 3 μs, the 150 kHz bandwidth will cause distortion of the signal at the beginning. Therefore it is proposed to use a digital oscilloscope with differential amplifiers for signal digitation. Differential amplifiers, rather than conventional amplifiers, are proposed because these permit the bucking out of any dc signals due to initial bridge unbalance so that only the dynamic signals are digitized.

It is proposed to use Tektronix Model 11401 digitizing oscilloscope together with two 11A33 differential comparators and a PS 5004 precision power supply to process the strain gage signals.

The model 11401 scope has a 500 MHz bandwidth with a time base with record durations ranging from 5.12 ns to 1024 sec. and a record length of 512 to 10,240 points. The sampling rate for digitation is 20 MS/sec. for single channel and 10 MS/sec. for dual channel operation in the chop mode. This digitation rate is just about what is needed and the 500 MHz band width is more than adequate, as is the record length of up to 10,240 points. The scope is fully compatible with microcomputers but also has internal storage capability.

The 11A33 differential comparators have vertical sensitivities from 1mV/Div to 10V/Div with a 10 bit (1024) digitizer. The offset voltage is $\pm$ 8V with 25 μV setability, giving an effective screen height of 16,000 divisions and permitting absolute DC measurement accuracies of $\pm$ 0.2% at a handwidth of 150 MHz. This is quite adequate for measuring the output of the strain gages, which is expected to result in voltage levels on the order of a hundred millivolts.

The final piece of equipment to complete instrumentation requirements is the PS5004 power supply. This power supply has a 0-20V floating output with 0.01% accuracy and has been designed for use with high-performance strain gage circuits. One power supply can be used to power both strain gage circuits.

The Tektronix scope has been selected because Tektronix offers a wider selection of accessories than do some other digital scope manufacturers. Particularly, the 11A33 differential comparator has features (1mV/Div sensitivity) not found among competitors. Also, Tektronix has a long history of supplying precision equipment that is reliable.

While other manufacturers make equally good timers and power supplies, the Tektronix models have been selected for convenience and consistency in maintenance/service contracts.

C. LAUNCHING DEVICE

A launching device is required to propel the impact bar toward the receiver bar with variable velocities that may reach as high as 100 ft./sec. (30.5m/sec.). The gas gun has been used successfully for this purpose by several investigators while Davies and Hunter have used explosive detonators (References 1,9,12,8). On the whole, the gas gun is safer and easier to use and is proposed for this project.

Figure 10 is a schematic of a typical gas gun. It consists of two pressurized chambers with the inner (smaller) chamber and its piston acting as a quick-release valve. Both chambers are pressurized with nitrogen to the desired pressure. The inner chamber pressure should be somewhat higher than the outer chamber pressure so that the piston is forced tightly against the front (right-hand) wall, thus sealing the barrel opening. When the fast-opening ball valve (B) is opened, the pressure in the outer chamber forces the piston to the left, thus quickly unsealing the barrel opening and propelling the impact bar from the barrel. A reasonably tight fit is required between the barrel and the impact bar to maintain alignment and to keep the gas from escaping around the impact bar; however, this should not be so tight that appreciable amount of energy is lost in overcoming friction.

Although operating pressures will generally be lower, both chambers should be designed to withstand 2500 psi (17.2 MPa) pressure in the event of malfunction or operator error where the maximum nitrogen tank pressure is applied to one or the other of the pressure chambers. The design presented in Figure 10 meets these requirements.

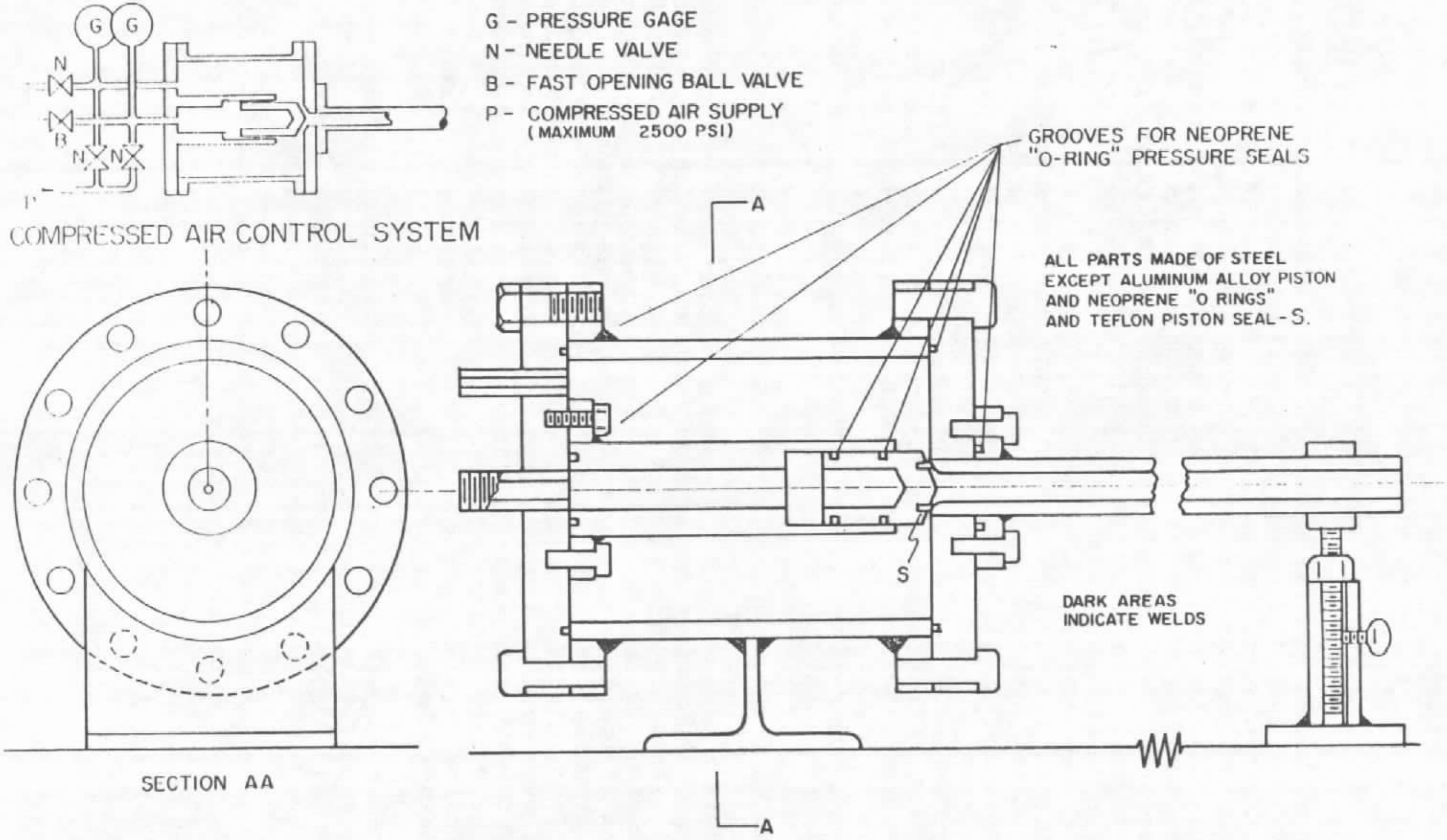


Figure 10. Gas Gun for Propelling the Impact Bar.

SECTION IV

WAVE PROPAGATION THEORY

In the loaded system, dynamic loading produces stresses and strains whose magnitude and distribution will depend on the material configuration and properties and also on the velocity of propagation of the strain waves through the material. When a force is first applied, its action is not transmitted instantaneously to all parts of the body; rather, stress waves and deformation radiate from the loaded region with finite velocity of propagation. In an elastic solid, there is more than one kind of wave and more than one characteristic wave velocity. At a great distance from the center of the disturbance (point of the load), it is assumed that all particles are moving either parallel to the direction of wave propagation (longitudinal wave) or perpendicular to this direction (transverse wave).

In longitudinal waves or waves of dilatation, the deformation field is only represented by longitudinal displacement and the effect of Poisson's ratio is not considered. As a result, the transverse waves or waves of distortion are ignored and are assumed to be zero if the impulse load is only applied in the longitudinal direction.

A. THEORY OF LONGITUDINAL WAVE PROPAGATION

To derive the equations of motion for an elastic homogenous media, it is necessary to examine the equilibrium of a small element. Since the application of the Hopkinson pressure bar test procedure is based on the longitudinal wave theory, the derivation of equation of motion will be in one dimensional space and time. Three kinds of independent wave motions are possible in bars: longitudinal, torsional, and flexural. Longitudinal and torsional wave motions result in the typical wave equation, while the flexural wave results in excitation or wave length dependency equation of motion. Since the test under consideration is based on longitudinal motion, the typical wave equation is obtained for one dimensional longitudinal motion.

Consider the free vibration of a rod with constant cross sectional area A, Young's modulus E, and unit weight ρ as shown in Figure 11. Two major assumptions are used in the derivation; namely, the stress is uniform over the cross sectional area, and the cross section of the bar remains plane during motion. The inertia forces caused by the lateral motions of particles are neglected, and there is no lateral stress present which will categorize the system as a longitudinal, one dimensional wave. This assumption is accurate as long as the wave length of the longitudinal wave is longer than the cross sectional dimensions of the bar.

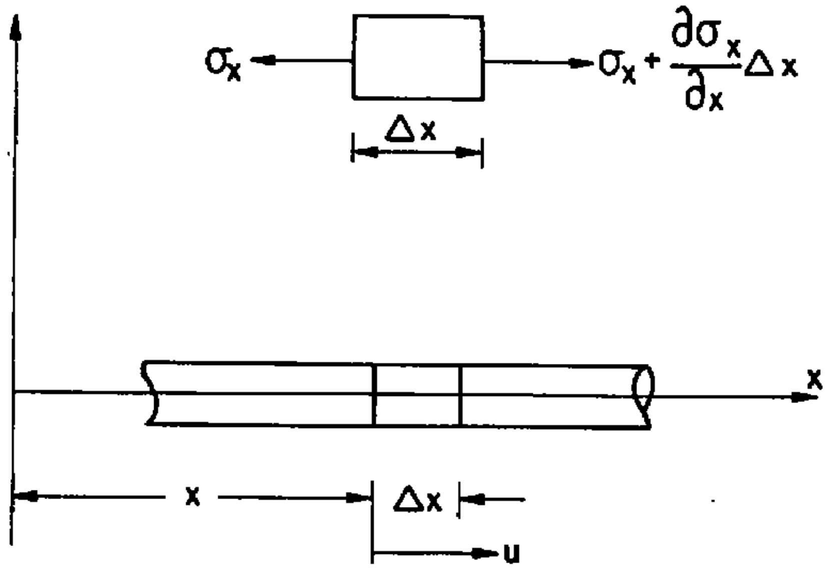


Figure 11. Equilibrium of Infinitesimal Longitudinal Bar.

The stress on a transverse plane at position x is σ_x and at $x + \Delta t$ has to be $(\sigma_x + \partial\sigma_x/\partial x)\,\Delta x$, therefore,

$$-\sigma_x A + \left(\sigma_x + \frac{\partial \sigma_x}{\partial x}\,\Delta x\right) A = F \tag{3}$$

If the displacement of the element in the longitudinal direction is designated as u, then Newton's second law of motion can be expressed for this system as:

$$-\sigma_x A + \sigma_x A + \frac{\partial \sigma_x}{\partial x}\,\Delta x\,A = \Delta x\,A\,\frac{\gamma}{g}\,\frac{\partial^2 u}{\partial t^2}$$

or
$$\frac{\partial \sigma_x}{\partial x} = \frac{\gamma}{g}\,\frac{\partial^2 u}{\partial t^2} \tag{4}$$

The strain-displacement relationship for longitudinal deformation without any Poisson effect can be utilized in stress-strain relationship. Therefore,

$$\sigma_x = E\,\frac{\partial u}{\partial x} \tag{5}$$

The above equation assumes a linear elastic material where the Young's modulus is constant. Differentiation of the above equation with respect to x will yield

$$\frac{\partial \sigma_x}{\partial x} = E\,\frac{\partial^2 u}{\partial x^2} \tag{6}$$

Combining Equation 4 with the above equation, while defining the mass density as $\rho = \gamma/g$, then

$$E\,\frac{\partial^2 u}{\partial x^2} = \rho\,\frac{\partial^2 u}{\partial t^2} \tag{7}$$

or
$$\frac{\partial^2 u}{\partial t^2} = c^2\,\frac{\partial^2 u}{\partial x^2} \tag{8}$$

where $C = \sqrt{E/\rho}$

where C is defined as the phase velocity or longitudinal wave-propagation velocity in a bar.

The solution of wave equation may be written in the form

$$u = f\ (Ct + x) + h\ \ (Ct-x) \tag{9}$$

where f and h are arbitrary functions. The solution represents a wave traveling in x-direction with velocity C. When a uniformly distributed compressive stress pulse of intensity σ_x and duration t_n is applied to the end of the bar, only a small region of the bar will initially experience the compression. As time increases, the compression stress will be transmitted to successive regions of the bar. The velocity of the transmitted wave from one region to another is the wave velocity C. The compressive stress will travel along the bar a distance Δx after a time interval Δt. At any time after t_n, a segment of the bar of length $X_n = Ct_n$ will constitute the compressed reign, and the amount of elastic shortening of this region will be given by the displacement of the end of the bar as:

$$u = \frac{\sigma_x}{E}\, x_n = \frac{\sigma_x}{E} Ct_n \tag{10}$$

The particle velocity is the ratio of displacement of particle to the duration of compressive wave; therefore,

$$\dot{u} = \frac{u}{t_n} = \frac{\sigma_x C}{E} \tag{11}$$

It is important to mention that the particle velocity depends on the intensity of the stress, but the wave propagation velocity, C, is only a function of material properties.

B. WAVE PROPAGATION AT DISCONTINUITIES

The longitudinal wave propagation theory requires a bar much greater in length than diameter and uniformity of stress in the cross section. If two different materials which have different wave velocity are in full contact, the wave will be divided into two parts at the interface. Due to wave velocity difference and cross sectional mismatch, some waves will be reflected and some will be transmitted.

Figure 12 shows the two bars with different cross-sectional area, mass density, and wave velocity. Since the stress is uniform the internal forces at the interface should be in equilibrium; therefore,

$$(\sigma_i + \sigma_r) A_1 = \sigma_t A_2 \tag{12}$$

where σ_i is the incident wave coming to the interface
σ_r is the reflected wave from the interface
σ_t is the transmitted wave to the second bar

Since the two bars are in full contact, continuity of displacement and velocity should be satisfied; therefore,

$$V_I = V_{II} \text{ or } V_i - V_r = V_t \tag{13}$$

where V is particle velocity

Combining the two above equations leads to

$$\sigma_r = \frac{\rho_2 C_2 A_2 - \rho_1 C_1 A_1}{\rho_2 C_2 A + \rho_1 C_1 A_1} \sigma_i \tag{14a}$$

$$\sigma_t = \frac{2\rho_2 C_2 A_1}{\rho_2 C_2 A_2 + \rho_1 C_1 A^1} \sigma_i \tag{14b}$$

In the Hopkinson pressure bar, the specimen is sandwiched between two long bars. If the two bars are made of the same material and have the same cross-sectional area (which is different from the specimen), there will be a transmission of an incident wave from the first bar to the specimen with some reflection. The specimen will transmit a wave to the second bar as well with some reflection from the second interface. As a result a number of reflections will be generated in the specimen. Figure 13 shows the location of the specimen within the two pressure bars. Using the above equation, the transmitted and reflected wave can be expressed as:

$$\overset{1}{\sigma_r} = \frac{\rho_s C_s A_s - \rho_b C_b A_b}{\rho_s C_s A_s + \rho_b C_b A_b} \sigma_i = -\alpha\sigma_i \tag{15}$$

$$\overset{s}{\sigma_t} = \frac{2\rho_s C_s A_b}{\rho_s C_s A_s + \rho_b C_b A_b} \sigma_i = \beta\sigma_i \tag{16}$$

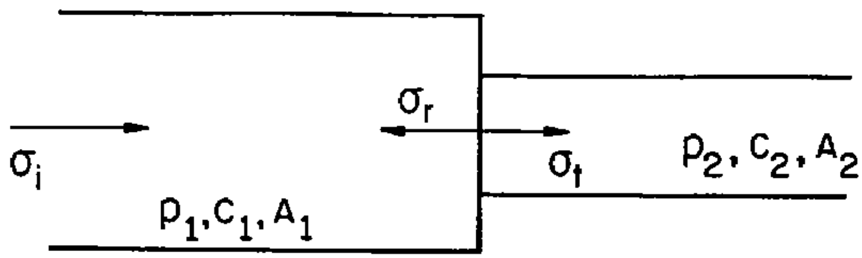


Figure 12. Wave Propagation at Interface.

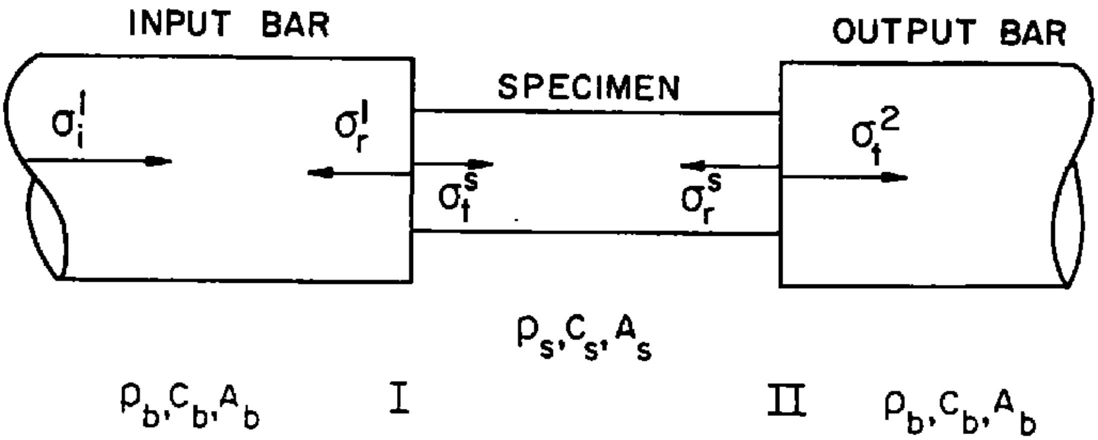


Figure 13. Wave Propagation at Three Bars Arrangement.

$$\sigma_r^s = \alpha\beta\ \sigma_i \tag{17}$$

$$\sigma_t^2 = \frac{2\ \rho_b C_b A_s}{\rho_s C_s A_s + \rho_b C_b A_b}\ \beta\sigma_i = \Omega\beta\sigma_i \tag{18}$$

Since the reflection of the wave in the specimen plays an important role in the test setup, the state of stress after each reflection will increase to a stable value. The state of stress in the specimen can be written as

$$\sigma_s = \beta\ (\alpha+\alpha^2 + \alpha^3 + \cdots +\alpha^n)\ \sigma_i \tag{19}$$

If n approaches infinity and using geometric series expansion while $\alpha < 1$, the stress will be in equilibrium as:

$$\sigma_s^e = \frac{\beta}{1-\alpha}\ \sigma_i \tag{20}$$

As n increases, the term $\beta\alpha^n$ decreases and approaches zero. The effect of $\beta\alpha^n$ may not be significant in a test measurement if $\beta\alpha^n$ is less than some tolerance.

Table 1 shows the effect of the ratio of the bar cross sectional area to the specimen. That ratio yields to the number of reflections required for equilibrium.

C. ANALYSIS OF STRAINS

Upon impact, compressive stress σ_i moves down the input bar (incident bar) and is partially reflected upon reaching the specimen. This reflected stress σ_r, due to the impedance mismatch at Interface I, moves back toward the impact surface. If a strain gage is mounted on the input bar, the incident strain as well as the reflected strain can be measured. Since the input and output bars remain in the elastic state at all times, the elastic strain, stress, and particle velocity can be determined at all times. If the specimen is small enough so that the transit time for the elastic wave is short, equilibrium throughout the specimen is rapidly established, and plastic deformation takes place uniformly within the specimen. The elastic bars at the ends of the specimen constrain the lateral plastic deformation somewhat due to friction; however, with a good surface finish on the bars, proper lubrication, and proper selection of specimen dimension, contact friction will be reduced. At Interface I, part of the input stress which the specimen can support is transmitted as σ^s. As the specimen strain hardens, a higher stress can be supported and σ^s increases

Table 1. Effect of Area Mismatch on Equilibrium Reflection*

A_b/A_s	α	β	Ω	Number of Reflection (n) Tolerance $\beta\alpha^n$ 0.05	0.02	0.01
9/4	0.8895	0.249	0.840	14	22	28
4	0.9363	0.255	0.484	24	37	50
5	0.949	0.256	0.390	31	49	62
7	0.983	0.258	0.280	45	68	87
9	0.971	0.259	0.219	56	87	111
21	0.998	0.261	0.095	137	213	271

* Bar Properties: $C_b = 2x10^5$ in/Sec (5000 m/Sec) $_b = 7.32x10^{-4}$ lb-Sec^2/in^4 ($2.4x10^{-3}$ kg-sec^2/m^4)

Specimen Properties: $C_s = 1.03x10^5$ in/Sec (2616 m/Sec)$_s = 1.87x10^{-4}$ lb-Sec/in^4 ($6.14x10^{-4}$ Kg-Sec^2/m^4)

while σ_r decreases as a function of time. The transmitted stress σ^s will travel through the specimen to Interface II. The reflected stress at Interface II will travel toward Interface I while transmitted stress will spread to the second bar and the strain gage mounted on the output bar will record the transmitted strain. The reflected part of σ^s at Interface II is reflected back and forth within the specimen and reaches the equilibrium distribution.

If the equilibrium is checked at Interface I and II, we have

$$(\sigma_i - \sigma_r)A_b = \sigma_t^s A_s \tag{21I}$$

$$(\sigma_t - \sigma_r^s)A_s = \sigma_t A_b \tag{21II}$$

the average stress in the specimen is then

$$\sigma_{ave} = \frac{1}{2}(\sigma_I + \sigma_{II}) = \frac{(\sigma_i - \sigma_r) + \sigma_t}{2}\left(\frac{A_b}{A_s}\right) \tag{22}$$

The stress at the interface cannot be measured; therefore, the strain gages are mounted such that they can be properly in phase in the two bars. The assumption is that the gage position will represent the interface behavior at a given stress level, and also the traveling time required for transmitted and reflected waves from interfaces to the strain gages has to be the same. If the bars are made of the same material, then the gages should be equidistant from the interfaces.

Knowing the strain at gage positions, the displacement can be calculated at two interfaces as:

$$U_I = \int_o^t C\epsilon_I dt = \int_o^t C(\epsilon_i - \epsilon_r)\, dt \tag{23a}$$

$$U_{II} = \int_o^t C\epsilon_{II} dt = \int_o^t C(\epsilon_t) dt \tag{23b}$$

The average strain in the specimen can be expressed as

$$\epsilon_s = \frac{U_I - U_{II}}{L} \tag{24}$$

where L is the length of the specimen. Substituting U_I and U_{II} into the above equation and assuming constant wave velocity in bars, the average specimen strain is

$$\epsilon_s = \frac{C}{L} \int_0^t (\epsilon_i - \epsilon_r - \epsilon_t)\,dt \tag{25}$$

The average force applied to the specimen can be expressed as the measured strains at gage location as:

$$P_{ave} = \frac{EA}{2} (\epsilon_i + \epsilon_r + \epsilon_t) \tag{26}$$

If the inertia term is ignored or is not present, it is assumed that the force at Interface I is equal to the forces at Interface II; therefore, specimen strain, stress, and strain rate can be expressed as:

$$\epsilon_s = \frac{-2c}{L} \int_0^t \epsilon_r\,dt \tag{27}$$

$$\sigma_s = E \frac{A_b}{A_s} \epsilon_t \tag{28}$$

$$\dot{\epsilon}_s = \frac{-2C}{L} \epsilon_r \tag{29}$$

It is important to mention all of the assumptions of the above formulation:

1. Stress, strain, strain rate are average values.
2. Bar behavior is elastic at all times.
3. No frictional effect at the interface between specimen and bars.
4. Inertia term is ignored.
5. System is conservative (no energy loss).
6. No lateral deformation and stress in bars.
7. The system is aligned such that there are no out-of-plane forces.

8. Stress and strain are uniform in the bar and specimen.

9. Equilibrium state in the specimen is established before the total duration of the test.

10. Properties of the bar and specimen are constants with respect to time.

Davies and Hunter studied the inertia effect of the specimen from a kinetic energy approach in 1963 (Reference 8). In their derivation of inertial stress, they assumed the strain rate as a function of time, and they developed the stress correction for radial and longitudinal inertia in terms of strain acceleration. The corrected stress with reference to the center of the specimen is expressed by

$$\sigma_s = \sigma_m - \rho\left(\frac{1}{12} L^2 + \frac{1}{8} \nu d^2\right) \ddot{\epsilon}_s \tag{30}$$

If the stress is measured at the back surface of the specimen, the corrected stress will be:

$$\sigma_s = \sigma_m + \rho \left(\frac{1}{6} L^2 + \frac{1}{8} \nu d^2\right) \ddot{\epsilon}_s \tag{31}$$

where σ_m is the magnitude of the measured stress and ρ, ν, and d are mass density, Poisson's ratio and diameter of specimen, respectively.

In practice, the strain rate in the specimen is not constant due to the plastic deformation of the specimen. Since the specimen will deform after reaching its yield point, the cross-sectional area will increase in the case of compression. The specimen will work harden and get stiffer as the strain increases. As a result the strain rate will decrease as the strain increases. Controlling the strain rate is not feasible for short specimens even though the variation is very small. To eliminate the inertial effect, one may change the dimension of the specimen with respect to the Poisson's ratio. Davies and Hunter employed the specimen of dimensions $= \sqrt{3/4}\nu d$ to eliminate the inertia term (Reference 8).

SECTION V

DESIGN OF HOPKINSON BARS

A. HOPKINSON PRESSURE BAR DESIGN

To design a Hopkinson pressure bar test apparatus to evaluate stress-strain relationship under different strain rates, all the effective variables which control the behavior of the elements have to be considered. The wave propagation theory is used in the elastic region to analyze the stress-strain behavior of composite material with different strain rates ranging from 10 per second to 10^4 per second. The following effective design variables have to be considered:

1. Type of material and its static mechanical properties (all direction elastic moduli and effective Poisson's ratios).
2. Concentration of reinforcement as volume fraction either by weight or volume and the spacing of reinforcement (fixed for a specific composite).
3. Specimen's diameter and its relation with Hopkinson pressure bars.
4. Specimen's length and its position in specimen holder.
5. Wave velocity in specimen.
6. The required time for wave to reach equilibrium (equilibrium transit time).
7. The specimen dimensions, mainly dependent on the failure mode of composite material.
8. Strain gage location for continuous reading of all traveling waves.
9. Impact velocity of striker bar as strain rate control variable.
10. Striker bar length, type, and cross section as well as the pressure gun system to accelerate the bar to a desired velocity.
11. Material used in the pressure bars and its capability of carrying the longitudinal wave.
12. Geometric dimension of bars (cross-section and length).

13. Frictional effect of contact (specimen with bars) which is a function of length, cross sectional area, and Poisson's ratio.

14. Effect of inertia terms from the bars due to impact.

15. Holding devices and their design geometry under shear, compression, and tension setups.

16. Duration of test and its effect on equilibrium transit time.

17. Consideration of stress concentration at the tip of each bar to ensure elastic behavior.

18. Damping mechanism of output bar to ensure continuous strain reading with no disturbance from the reflection of the transmitted wave.

19. Measuring devices (strain gage type, signal conditioner, amplifier and filter, data recorder, computer) and their capability of performing under high frequency.

B. COMPOSITE MATERIAL

Most composite materials developed thus far have been fabricated to improve mechanical properties such as strength, stiffness, toughness, and high-temperature performance under different types of loading (static or dynamic). The mechanical properties of composites strongly depend on the geometry of the reinforcement with respect to external loads. The volume fraction and concentration of reinforcement plays an important role in mechanical behavior, particularly under dynamic loading, and the orientation of the reinforcement affects the isotropy of the system. In continuous-fiber-reinforced composites, unidirectional or cross-ply reinforcement introduces anisotropy in the system. Moreover, the primary advantage of reinforced composite system is the ability to control anisotropy by design and fabrication. Due to the anisotropic behavior of a composite system, the mechanical behavior will depend on fixed independent constants. In addition, the material properties are dependent on the type and rate of loading.

The components of the Hopkinson Pressure Bar test setup should be designed such that they are capable of determining the longitudinal and transverse moduli of composite material under all types of loading, namely, compression, shear, and tension. The selection of specimen shape and size is governed primarily by the type of loading, orientation, volume fraction, and concentration of reinforcement for such a testing.

Consider carbon-carbon composite material with spacing of fibers in the range of 0.025 - 0.05 inches (0.635 - 1.27 mm). In order to consider the effect of fibers and their interaction with the matrix, there should be at least ten fiber bundles present. Therefore, the smallest specimen size should be greater than or equal to 0.25 inches (1.27 mm) in circular or 0.25 inches in rectangular cross section. It is important to note that specimen size depends also on the failure mode (fiber, matrix, and matrix-fiber interface failure).

Since all the static properties of carbon-carbon composite are not known at the present time, realistic values should be assigned to the governing design variables. The mass density of composite is measured to be 1.87×10^{-4} lb-sec^2/in^4 (6.14×10^{-4} Kg-Sec^2/m^4). The modulus of elasticity plays an important role in the wave velocity and eventually affects the duration of equilibrium in the specimen. The modulus of elasticity of 91 percent carbon fiber is reported to be 6 million psi (41 GPa). The design value of Young's modulus for chapped carbon reinforcement is recommended to be 2.5 million psi (17.2 GPa) while the tensile strength is 30 ksi (206.5 MPa). In this study, the elastic modulus of the specimen is chosen to be 2 million psi (13.8 GPa) which leads to elastic wave velocity of 103,000 inch/sec (2616 m/sec). The chosen wave velocity may be low compared to the actual velocity of waves in carbon-carbon composite, but the Hopkinson pressure bar should be designed to be able to test other composite materials which may have lower wave velocity than carbon-carbon composite.

C. DESIGN OF COMPRESSION TEST

The dimensions of the specimen will dictate the bar's dimensions in terms of length and diameter. It is important to use the least amount of composite material possible as long as this does not violate any assumption in the Hopkinson bar test setup and elastic wave propagation. Consideration of the number of fiber bundles in the specimen leads to the diameter of composite specimen to be selected at 0.5 inches (12.7 mm); at least 20 fiber bundles are thus included in the specimen. To prevent any local and/or global buckling of the specimen, the length should be short as compared to the diameter (L/D=1/2). The frictional effect of contact (specimen and bars) required that the ratio of length to the diameter be small. Therefore, the length of the specimen is chosen to be 0.25 inches (6.35 mm).

Consider three bars (striker, incident, transmitter) made of metal alloy with outer diameters of 3/4 inch (19 mm) with the following properties:

$$\rho = 7.32 \times 10^{-4} \ \frac{\text{lb-Sec}^2}{\text{in}^4} \quad (2.4\times10^{-3}\ \text{Kg/Sec}^2/\text{m}^4)$$

$$E = 29 \times 10^6 \text{ psi (200 GPa)}$$

$$C_b = \sqrt{E/\rho} = 2 \times 10^5 \text{ in/sec (5080 m/sec)}$$

where ρ , E, C_b are the mass density, elastic Young modulus, and elastic wave speed of bars, respectively.

As was described in Section II, the loading pulse in this design is initiated by axial impact from the striker bar which is accelerated to impact velocity. The striker bar is of the same material and has the same diameter as the pressure bars (incident, transmitter). The striker bar produces a pressure pulse of constant amplitude (σ) while the duration (T) of loading is dependent upon the length of the striker bar. After the initial impact, the pressure is unloaded in the first bar (incident bar) as the compression wave, reflected as a tensile wave from the free end of the striker bar, returns to the impact face. Thus, the duration of the pulse in the incident bar is twice the time required to travel in the striker bar; i.e.,

$$T = 2\ L_{st}/C_b \tag{32}$$

where L_{st} is the length of the striker bar.

The compressive loading pulse travels through the incident bar to reach the specimen; a portion of the pulse is reflected from the interface, while part is transmitted through the specimen due to impedance mismatch. The wave transmitted to the specimen will have numerous internal reflections until it reaches an equilibrium state. The response of the test is mainly dependent upon the uniformity of the stress or deformation in the specimen. Such a uniformity can be reached if equilibrium in the specimen is established. The duration of the loading pulse should be longer than the equilibrium state of transit time in the specimen. If the Hopkinson bar diameter is chosen to be 0.75 inches (19.1 mm) the ratio of the bar cross sectional area to the area of the specimen is 9/4. Therefore, 28 reflections are required before an equilibrium state within a 0.01 tolerance is reached (Table 1). Thus, the equilibrium transit time, calculated from the following equation, is 68 microseconds:

$$t_s^e = n \frac{L_s}{C_s} \tag{33}$$

where:

t_s^e = equilibrium transit time

L_s = length of specimen
C_s = wave speed in specimen

Since duration of loading pulse (T) is greater than or at least equal to equilibrium transit time, then:

$$T > \frac{nL_s}{C_s} \qquad \text{where } T = \frac{2\,L_{st}}{C_b}$$

$$\text{then} \qquad L_{st} > \frac{nC_bL_s}{2C_s} \tag{34}$$

Therefore,

$$L_{st} > \frac{28(2x10^5)(0.25)}{2\ (1.03x10^5)} = 6.80"(0.173\ m)$$

Thus, the striker bar is chosen to be 1.5 feet (0.46 m) long (which produces a pulse with the duration of $1.8x10^{-4}$ seconds) since it is desired to have a longer striker bar for a longer duration of induced stress wave. Long duration is the controlling parameter for equilibrium transit time; this may be increased by lower values of elastic modulus or wave velocity. Therefore, this design is capable of testing composite or conventional materials with lower wave velocity.

For the gage to read, without interference, continuous strain at the incident bar (as incident and reflection strain), it should be positioned so that the distance between the gage and the specimen is greater than the length of the striker bar. Therefore, it is positioned 3 feet (0.91 m) from the specimen. The reflection of the first wave from the interface should not interfere with the coming wave from the striker bar at the gage position. The incident wave, measured from the incident gage, takes 180 microseconds to reach the specimen and takes 180 microseconds to reach equilibrium. The last reflection wave from the specimen takes 180 microseconds to reach the incident gage. The sum of these times should be less than the time required for the second wave from the striker bar to reach the specimen. Considering the distance between the incident gage and impact point of incident bar to be x,

then

$$\frac{2\,L_{st}}{C_b} + \frac{X}{C_b} > \frac{2\,L_g}{C_b} + {}^{e}t_s \tag{35}$$

Therefore the incident bar should be at least 4.5 feet (1.37 m) longer than the length of the gage to the specimen. Thus, the incident bar is chosen with a length of 9 feet (2.74 m). The transmitted wave in the transmitter bar should measure both the incident and the reflected waves simultaneously. Since the two bars are of the same material and have the same diameter, the transmitted gage is positioned 3 feet (0.91 m) from the specimen.

To allow all the transmitted waves generated from the specimen to go through the transmitted strain gauge, the length of the transmitter bar (output bar) should be greater than 3 feet (0.91 m). A damper is designed to capture the transmitted wave to ensure no reflection from the free end of the output bar. A damper consists of a sand box positioned at the end of the output bar which goes 5 inches (127 mm) into the box. To ensure continuous strain reading with no reflection from the sand box at the transmitter stain gage, the distance between the gauge and damper multiplied by two should be larger than the equivalent distance of specimen equilibrium transit time ($t_s^e C_b$).

$$L_t = 2x12 + \frac{1}{2} (68x10^{-6})(2x10^5) + 5 = 35.8" \ (0.91 \ m)$$

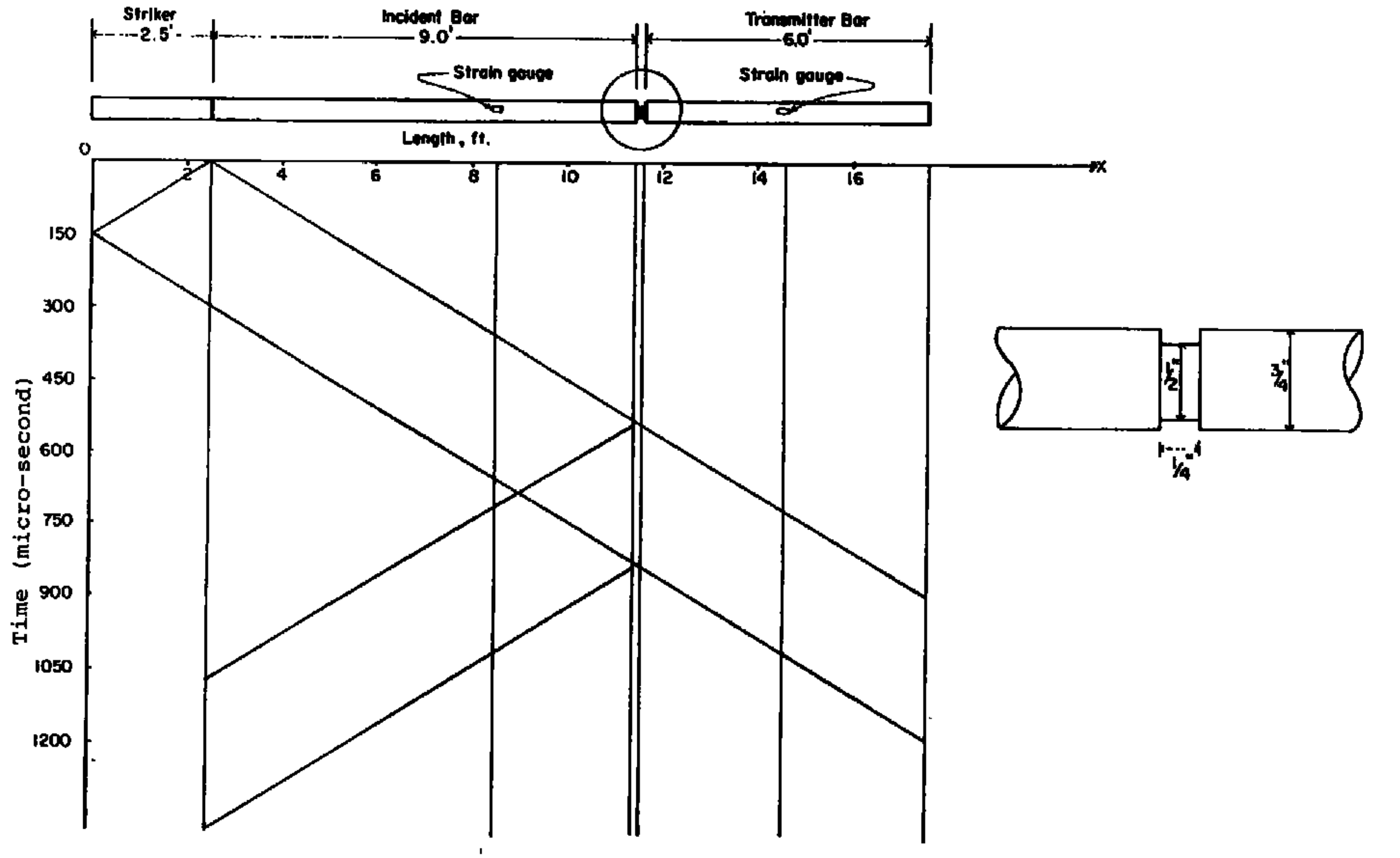
Therefore, the output bar is chosen to be 6 feet (1.83 m) long. The transmitter and incident bars length are chosen to be longer than required for testing carbon-carbon composite material; this increase of length of the bars allows the user to test somewhat softer materials which have lower wave velocity, or stiffness. The Lagrange diagram (x-t) and position of the specimen in the compression setup is shown in Figure 14.

Due to anisotropy of composite material, the mechanical behavior is different in longitudinal directions than in the transverse directions. The longitudinal stress-strain relationship is measured with the fiber direction in the direction of the bars while transverse properties are measured with the fibers perpendicular to the loading axis.

D. DESIGN OF SHEAR TEST

Spacing and concentration of fibers constrain the specimen size to at least 0.25 inch (6.35 mm) thickness. However, in order to minimize the amount of material required for testing, the specimens should be as small as possible. Therefore, a rectangular box specimen is considered for both the interlaminar and transverse shear test.

The shear stress required to cause failure along the fiber direction is called interlaminar shear if the loading direction



HEAR

Figure 14. The Compression and Shear Hopkinson Bar and Its Lagrange Diagram.

is parallel to the fiber direction. If the loading direction is perpendicular to the fiber direction it will create shear stress in the transverse direction. Figure 15 shows the dimensions and position of the specimen between the two pressure bars.

As was described in Section II, the interlaminar shear measurement may not be consistent on repeated tests due to spacing of fibers in the specimen. The failure surface should be examined after each test. The specimen may fail under different failure modes, namely, matrix failure, fiber failure, matrix-fiber interface failure, or a combination of fiber and matrix failure. Therefore, special attention should be given to the stress-strain relationship under the interlaminar shear test. Figure 16 shows the location of two bars on the specimen and the failure direction of each type with respect to fibers' positions and spacing.

The ratio of contact area between the specimen and the bar is 3.63. This ratio requires 50 reflections before it is in an equilibrium state within the tolerance of one percent of original stress initiated in the specimen (Table 1). Therefore, the equilibrium transit time, calculated from Equation 33, is 121 microseconds. As mentioned in the compression design, the striker bar length controls the duration of pulse which should be more than equilibrium transit time. Thus, the striker bar length has to be greater than 12 inches (0.3 m). A 1.5-foot (0.46 m) striker bar was used in the compression test and is adequate for the shear test. Since the ratio of contact areas and equilibrium transit time in the compression test are close to those in shear, the lengths of pressure bars in compression setup are adequate in shear test as well while the diameter of pressure bars in shear setup is 0.5 inches (12.7 mm). The shear Hopkinson pressure bar arrangement is the same as compression setup. Figure 14 shows the Lagrange diagram and relative position of the specimen between the bars. The details of the specimen holder are shown in Figure 15 for the two loading configurations.

E. DESIGN OF TENSION TEST

1. Design of Pressure Bars

As mentioned before, the diameter of the specimen should be designed such that there are as many as 20 or more fibers present in the cross section. There should also be a holding device to transfer the tension wave through the specimen with no slip or release of stress waves between the specimen and the holding device. The wave, induced by the impact of the striker bar on the input bar, is a compression wave. The device should be designed in such a way that this compression wave transforms to a tension wave. The design described in Section II using a split collar meets this objective. However, the area of the collar should be much larger than the area of the specimen to transfer

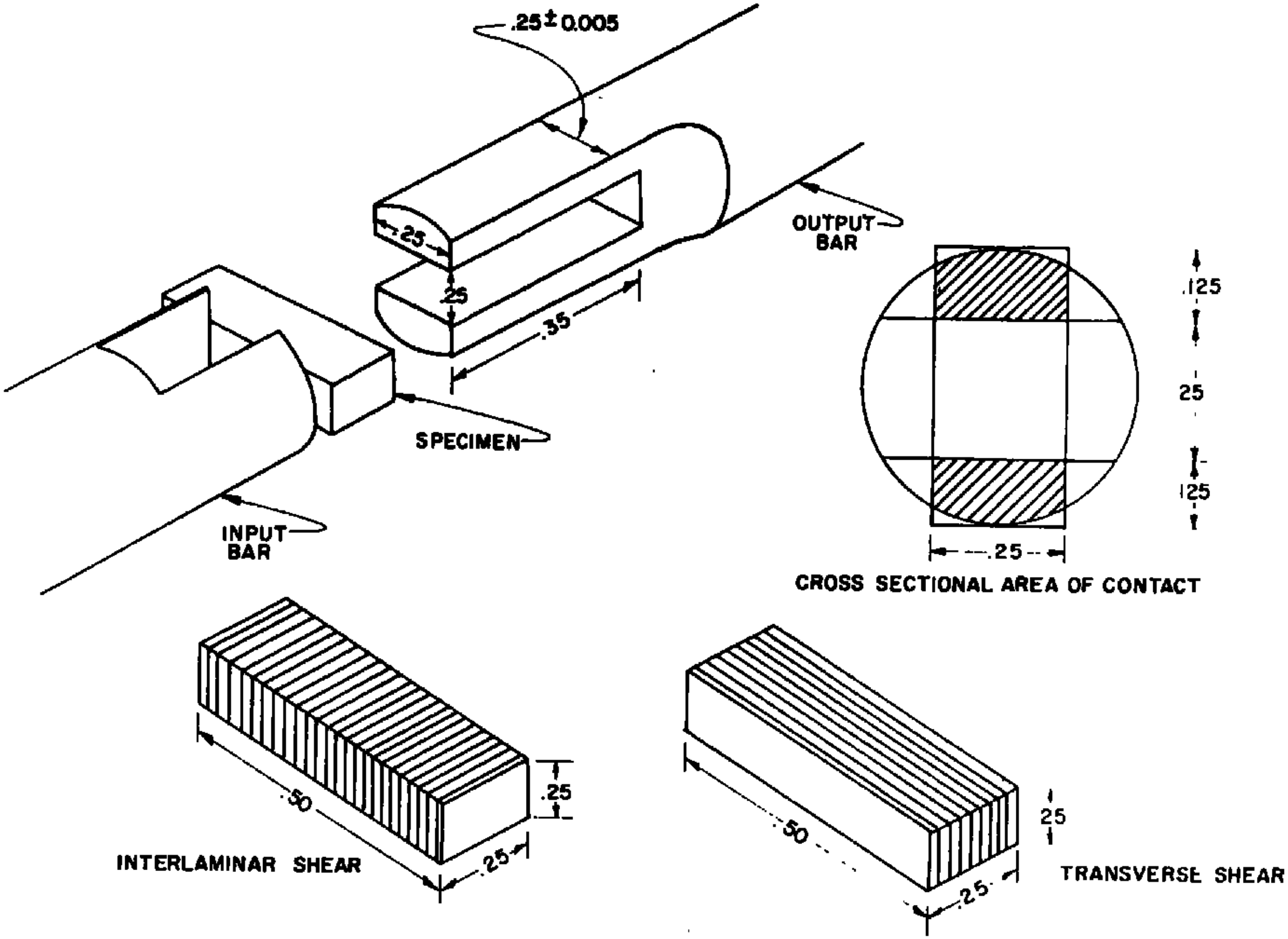


Figure 15. Shear Specimen.

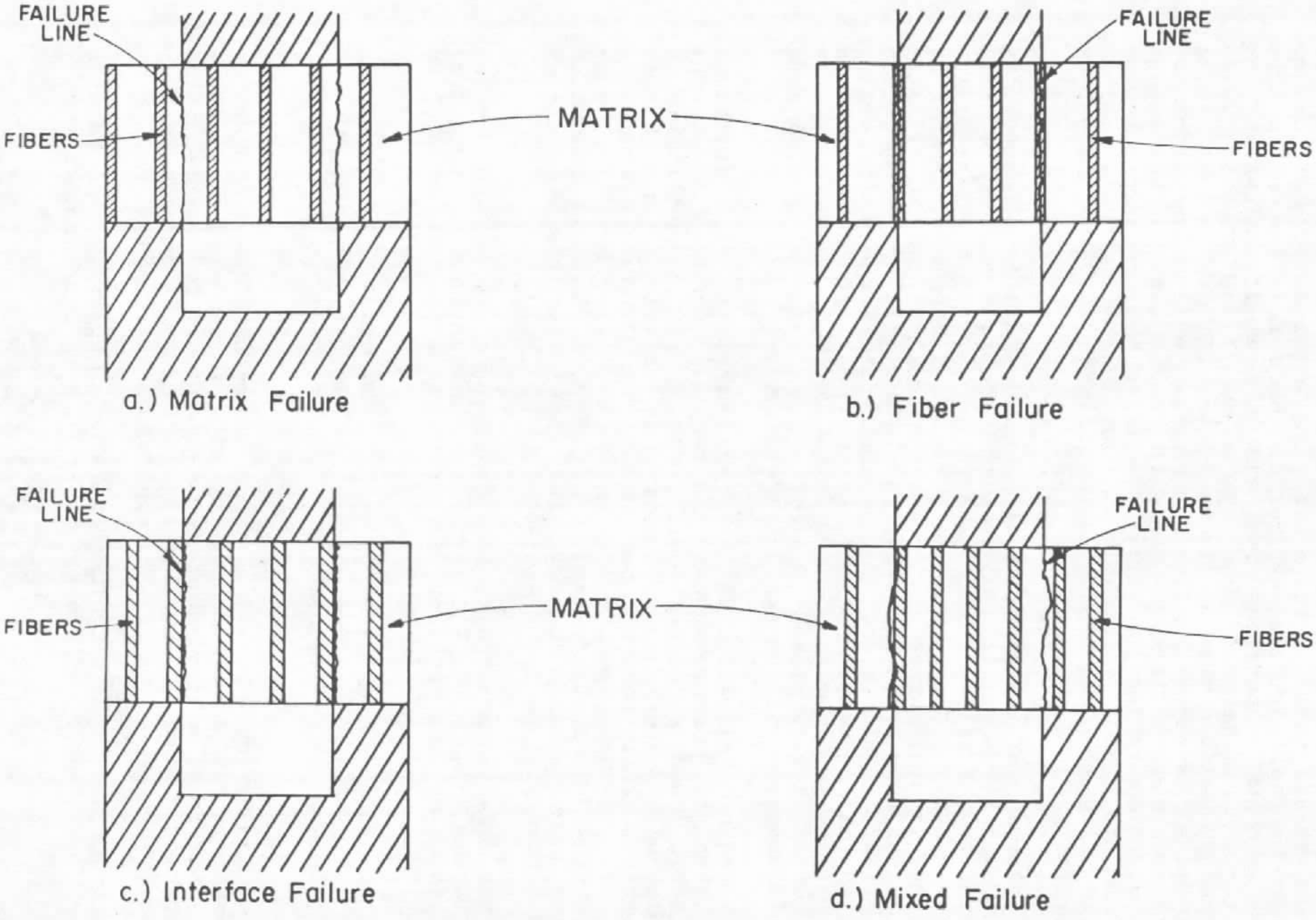


Figure 16. Possible Failure Modes In Interlaminar Shear.

all the stress waves. Therefore, the compressive wave can go through the split collar and reflect back from the end of the second bar as a tension wave, but the split collar has no resistance to a tension wave. As a result, all tension waves will be transmitted through the specimen. Since the area of the split collar is not equal to the bar area, an impedance mismatch exists and some reflected wave will travel back to the impact surface. This reflection forces the first bar to be long enough in order to obtain continuous reading of transmitted strains. Figure 17 shows the schematic specimen holder and the split collar position and geometry.

Selection of the diameter of specimen dictates the geometry of the bars. Since the area of the specimen has to be small compared to the split collar area, the specimen diameter is chosen to be 1/3 inch (8.5 mm); enough fiber bundles will be included in this specimen cross-section to reduce off-axis effects due to unsymmetric fiber bundle distrubtion to negligible proportions. To satisfy the requirement of the split collar area, the bar diameter should be at least 3/4 inch (19 mm). As a result, the ratio of the split collar area to the bar area is 0.93 (which is very close to unity) and the ratio of the bar area to specimen area will be approximately five.

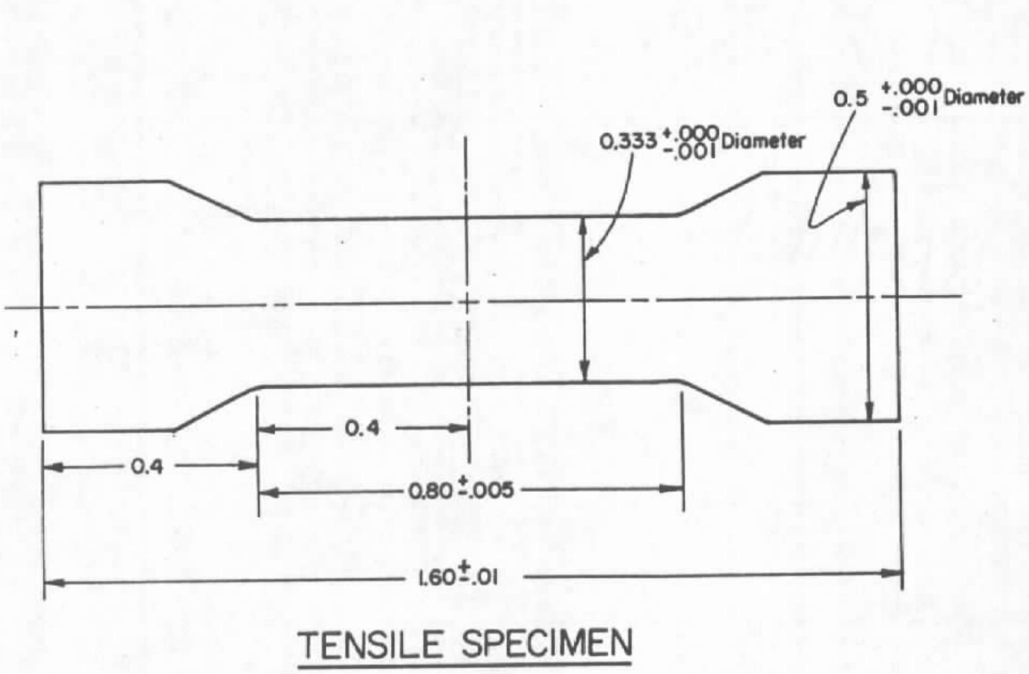
Impedance mismatch of bar and specimen will introduce reflection and transmission of the tensile wave from and to the specimen. These reflections will continue until equilibrium is established. Due to the area and material mismatch, 62 reflections will be required before equilibrium is obtained Table 1. From Equation 33, the time required for such equilibrium is 602 L_s microsecond. If the effective length of tension specimen is 0.5 inch (12.7 mm), then the equilibrium transit time will be 301 microseconds.

The duration of impulse load should be at least equal to the equilibrium transit time without any interference. Therefore, the length of the striker bar from Equation 34 should be

$$L_{st} > \frac{62(2\times10^5)(0.5)}{2(1.03\times10^5)} = 30.01" \ (0.76 \text{ m})$$

A striker bar 3 feet long (0.92 m) may be difficult to implement in the actual test setup with a conventional pressure gun. Therefore, a special pressure gun should be designed which is capable of accelerating the 3 feet (0.92 m) long striker bar to the desired velocity at the point of impact.

Figure 18 shows a typical Lagrange diagram for the tension test. The length of the first bar (L_1) is dependent on the



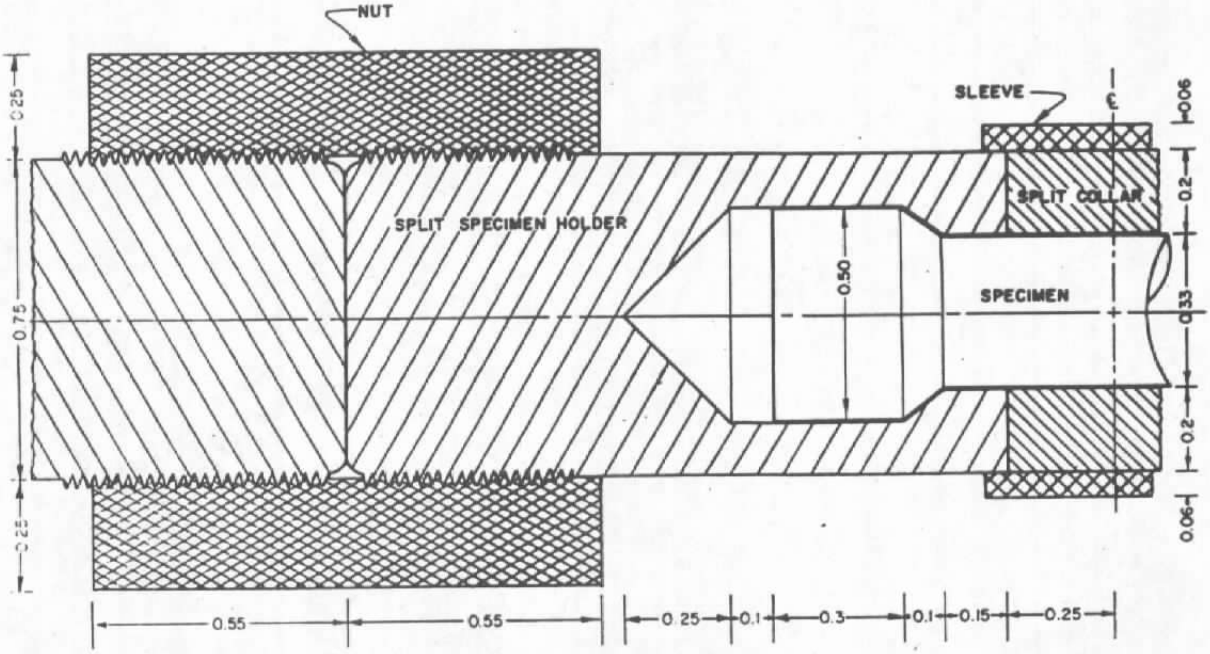


Figure 17. Tension Specimen and Its Mounting.

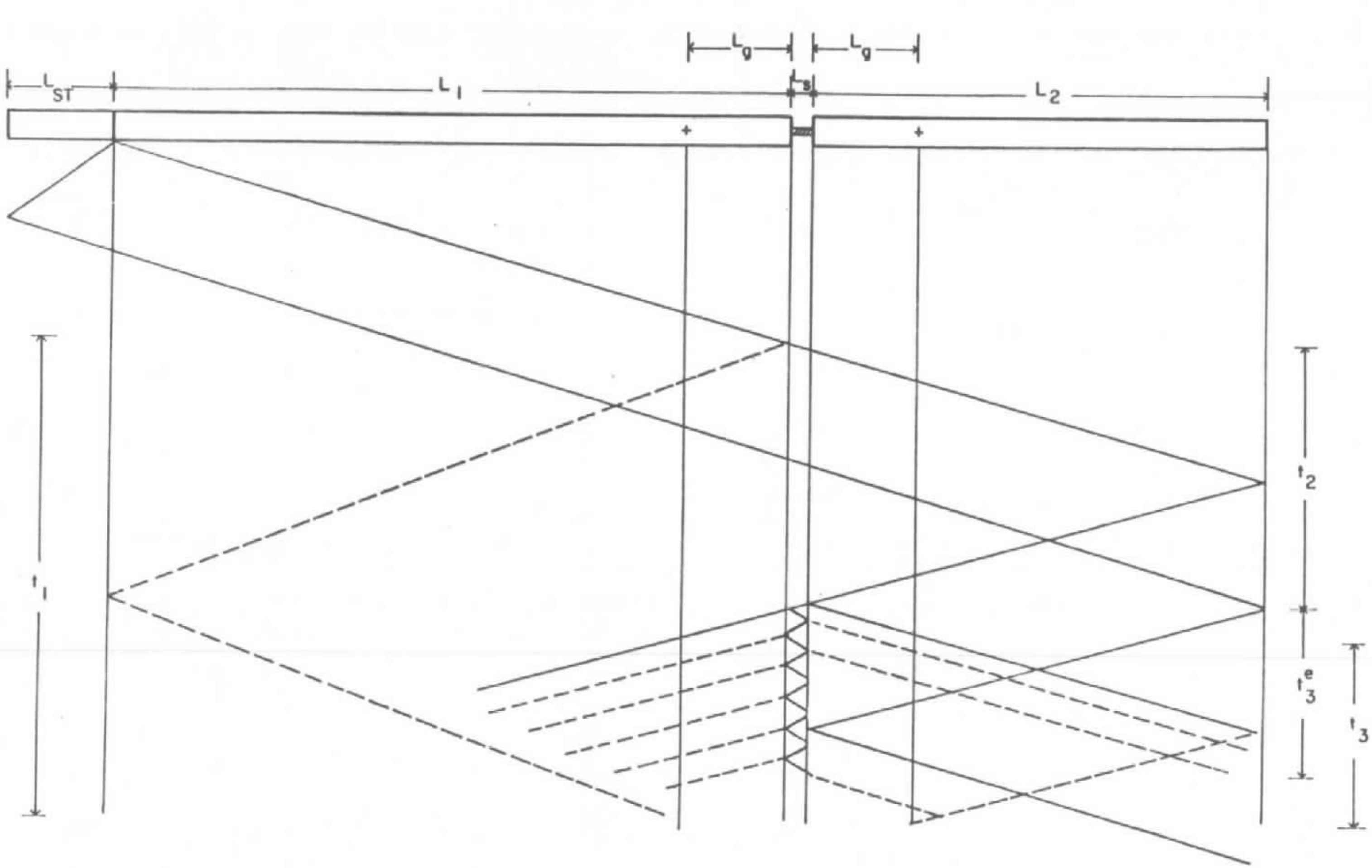


Figure 18. Lagrange Diagram for Tension Tests.

reflection of the compressive wave at the interface and collar, and is also dependent on the length of the second bar. If the gages are equidistant from the specimen in the two bars (L_g) then the required time of reflection (t_1) has to be greater than the time of travel of the wave in the second bar as well as the equilibrium transit time of the specimen. This constraint is enforced to eliminate interference in the first bar gage.

$$t_1 > t_2 + t_s^e + t_g \tag{36}$$

The reflection of the tensile wave from the specimen should not interfere with the gage reading while the tensile wave is reflected from the free end of the second bar until the equilibrium is reached in the specimen; therefore:

$$t_3 > t_s^e \tag{37}$$

Substituting the time in terms of wave speed and length, the above two equations can be expressed as

$$\frac{2L_1 - L_g}{C_b} > \frac{2L_2}{C_b} + \frac{nL_s}{C_s} + \frac{L_g}{C_b} \tag{38}$$

$$\frac{2(L_2 - L_g)}{C_b} > \frac{n\,L_s}{C_s} \tag{39}$$

where L_1 = length of first bar

L_2 = length of second bar

L_g = distance between gage and specimen

C_s = speed of wave in specimen

C_b = speed of wave in bar

n = number of reflections in the specimen before equilibrium.

Solving the above two constraint equations in terms of bar length, we will have,

$$L_1 > L_2 + L_g + \frac{nL_sC_b}{2C_s} \tag{40}$$

$$L_2 > \frac{nL_sC_b}{2C_s} + L_g \tag{41}$$

combining the above two constraint equations at the limit,

$$L_1 > L_2 + L_2 = 2\ L_2 \tag{42}$$

The above equation requires the length of the first bar to be twice the length of second bar. Since bars are in general not available in lengths greater than 12 feet (3.66 m), the first bar is chosen to be 12 feet (3.66 m) (or longer, if possible) and the second bar has to be 6 feet (1.83 m) (or longer). The gage location will be 3 feet (0.91 m) from the specimen in both the first and the second bars. Selection of 6 feet (1.83 m) long second pressure bar satisfies the second constraint given by Equation 42. A effective tensile specimen length of 1/2 inch (12.7 mm) has been selected (see Figure 17) which is also the length of the split collar. With the proposed specimen and bar diameters, 62 internal reflections are required to reach equilibrium within 1 percent. This condition can be met if the second pressure bar is 6 feet (1.83 m) long.

The dimensions of the specimens and Hopkinson pressure bars for different types of loading are summarized in Table 2. A cylindrical specimen shape is used in compression test setup while the tension specimen is chosen to be cylindrical dog bone configuration to ensure that the location of failure is near the middle of the specimen. In addition, the dog bone configuration allows the specimen holder to have a larger grip surface for the transmission of tensile waves through the specimen. The shear specimen is considered to be rectangular parallelepiped shaped.

2. Design of Threaded Connection

The specimen holder and the pressure bars should be in intimate contact so that all traveling (compression or tension) waves are able to go through the contact region without interference. The connection is designed such that the incoming high intensity stress wave does not produce plastic deformation in the threads. The connection should be tight to prevent any relative slip between the nut and bars (see Figure 17). To ensure full contact, a constant torque is applied on the nut to create an initial stress at the contact surface. The magnitude of the initial stress should be the same in both interfaces (i.e., at both ends of the specimen holder) for a consistent reading of strain at the gages. Since the cross-sectional area and material of the specimen holder and bars are the same, there is no impedance mismatch at the contact. As a result, no reflection will take place at the interface.

Table 2. Hopkinson Pressure Bars and Specimen Dimensions

Loading Type	Diameter of the Bars (in.)	Striker Bar Length (ft.)	Specimen Configúration Dimension (in.)	Input Bar Length (ft.)	Output Bar Length (ft.)	Strain Gage Locations from Specimen (ft.)
Compression	3/4	1.5	Cylindrical D=1/2, L=1/4	9.0	6.0	3.0
Shear	1/2	1.5	Rectangular Cube 1/4 x 1/4 x 1/2	9.0	6.0	3.0
Tension	3/4	3.0	Dog Bone D=1/3, L=1.16	6.0	12.0	3.0

A number of variables should be considered when preparing the proper design for a connection. These design variables are listed as:

1. Thread type.

2. Nut material and its strength.

3. Effective shear area of thread.

4. Number of threads.

5. Size of pitch.

6. Stress concentration.

7. Fatigue life of threads and nut.

8. Tightness of bar and specimen thread to the nut.

Threaded joints fail for two reasons: (1) a high stress concentration factor caused by the design of the thread form and (2) a high stress (load) on the first few threads of the nut. (A major part of the load tends to be transferred from the bar to the initial threads of the nut as it is loaded.) Figure 19 shows three types of thread in common use. Whitworth threads have shown a 16 percent increase in fatigue life over American standard threads because of their rounded roots. The modified American Standard threads have shown still further increase in fatigue life due to special larger root radii.

The problem of high stress on the first few threads of the nut can be controlled by using higher strength materials; this would reduce the number of threads required and would increase the fatigue life by a factor of two. The problem due to stress concentration is solved using appropriate thread shape; i.e., the modified American Standard.

The threads transfer the tensile and compressive stress wave to the bar and specimen holder. The shear area which resists the applied load is at the thread base and is dependent upon the pitch size. The shear area of one pitch is calculated based on the radius measured from either the bottom (b) of the thread or the middle (m) of the thread as:

$$A_{sh}^{b} = \left(\frac{7p}{32}\right) \sqrt{16p^2+9\pi^2(1-\sqrt{3}p)^2} \tag{43a}$$

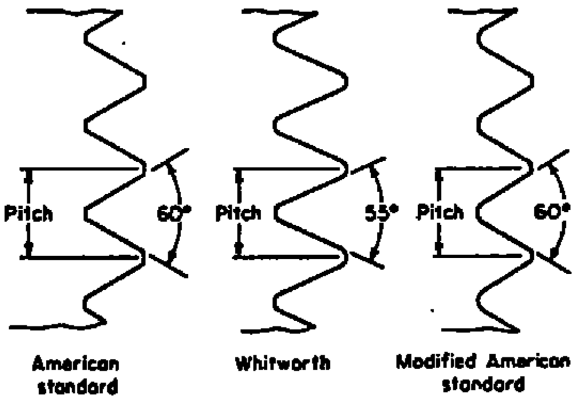


Figure 19. Thread Type Profiles

$$A_{sh}^{m} = \frac{p}{16}\sqrt{64p^2+9\pi^2(2-\sqrt{3}P)^2} \tag{43b}$$

The above equations are based upon information in Figure 20, illustrating modified American Standard threads (rounded root). If the stress distribution is uniform on all threads, then the total shear area will be nA_{sh}, where n is the number of threads in contact.

If a traveling wave with a magnitude of σ_i is present at the interface, then the shear force created in the threads will be $A_b\sigma_i$. For such a force to be applied on the threads without any plastic deformation or failure, the total shear area should be at least equal to the bar area (A_b); i.e.,

$$A_b\sigma_i < nA_{sh}\sigma_i \tag{44}$$

Table 3 shows the variation of pitch size and the corresponding number of threads required to transfer the incoming wave stress.

$$n = \frac{0.4418}{A_{sh}^{b}} \qquad L = np$$

How well the connection fits depends upon the selection of the pitch of the threads. Coarse thread size means less number of threads are required but also means that there will be gaps at the threads and that there will be slippage caused by bidirectional stresses. Also, using coarse threads means that the bar's cross-sectional area will be reduced. Using very fine threads means that there will be a greater number of threads, leading to a longer nut configuration. However, the stress is not spread across the threads uniformly; most of it is concentrated on the first few threads. Therefore, to ensure that the connection fits and that the amount of threads is kept to a minimum, a pitch size of 1/20 inch (1.27 mm) is recommended with 8 threads. The thread length would then be 0.4 inch (10.2 mm). Figure 21 shows the profile of the connection and the nut position and size.

F. STRESS DISTRIBUTION

As mentioned before, the impact of the striker bar on the input bar produces an initial stress wave. The magnitude of such a stress wave depends upon the velocity of the striker bar. Assuming the striker bar and the pressure bars are of the same

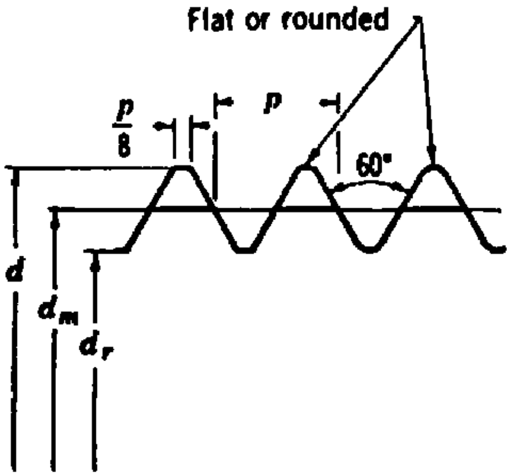


Figure 20. American Standard Unified Thread

Table 3. Variation of Pitch Size on Shear Area.

P(in)	A^{b}_{sh} (in^2)	A^{m}_{sh} (in^2)	n^b	n^m	L^b (in)	L^m (in)
$\frac{1}{10}$	0.1705	0.1076	2.59≈3	4.106≈5	0.3	0.5
$\frac{1}{16}$	0.1149	0.06965	3.85≈4	6.34≈7	0.25	0.4375
$\frac{1}{20}$	0.09416	0.05635	4.69≈5	7.84≈8	0.25	0.4
$\frac{1}{32}$	0.06094	0.0358	7.25≈8	12.33≈13	0.25	0.40625

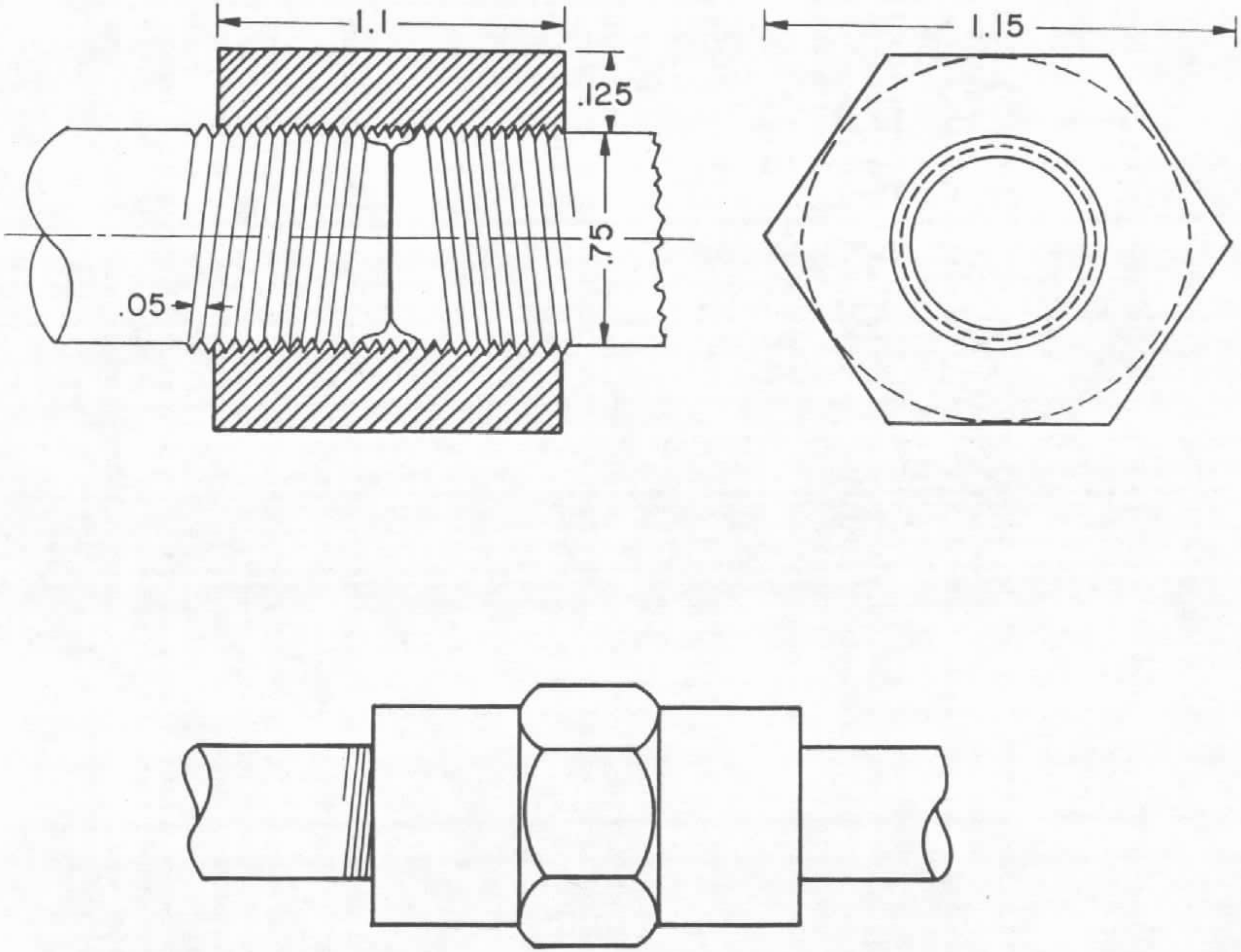


Figure 21. Threaded Specimen Holder Connection.

material and cross section, simply considering momentum and strain energy will show that the maximum strain in the pressure bars ϵ_{max} is given in terms of the impact velocity V by:

$$\epsilon_{max} = V/2C \tag{45}$$

Since the pressure bars are assumed to be linear elastic, the maximum stress due to impact will be:

$$\sigma_{max} = \rho CV/2 \tag{46}$$

The bar strain, which is generated by impact, is controlled by the velocity of striker bar. Consequently, the reflection wave caused by impedance mismatch at the interface will also be proportional to the pressure applied at the pressure gun. Therefore the strain rate of loading in the specimen is controlled and can be measured from the reflected waves. Due to the specimen-bar impedance mismatch, the stress concentration at the interface will be critical. The state of stress in the specimen and interface is governed by Equation 20 as:

$$\sigma_s^e = \frac{\beta}{1-\alpha}\sigma_i \tag{47}$$

Substituting the values of β and α in terms of wave velocities and cross sectional area, the stress concentration, governed only by the area mismatch, is:

$$\sigma_s = \frac{A_b}{A_s}\sigma_i = K\sigma_i \tag{48}$$

Table 4 shows the magnitude of such a stress concentration factor (K) for a different loading test setup.

The stress concentration at the tip of the pressure bars should be designed such that the yield stress is more than the actual stress level to satisfy the linear elastic assumption. Therefore, the yield stress at the tip of the pressure bars should be at least 3.5 times the initial stress created by impact for the shear test. A hardening of the pressure bars (which can be done locally at the tips of the bars) will increase the strength of the bars.

Table 4. Stress Concentration Factor.

Loading	A_b	A_s*	K
Compression	$\pi(3/8)^2$	$\pi(1/4)^2$	9/4
Shear	$\pi(1/4)^2$	$\frac{2\pi+3\sqrt{3}-6}{96}$	3.44
Tension	$\pi(3/8)^2$	-	1.4

*Contact area

G. CALIBRATION

In performing tests, the reflected and transmitter strain measurement are required to define the strain and stress in the specimen. These two strains are measured at the same time by placing the strain gages on the incident and transmitter bars equidistant from the specimen. Two gages on opposite sides of each bar record the direct pulse without any bending effects being present. The bars are long enough to permit observation of the entire loading event without interruptions caused by the wave reflection from the free end. The Hopkinson bar test procedure assumes longitudinal loading only; therefore, the striker bar and pressure bars should be aligned so that there is no out of plane loading or interference. The alignment should be checked carefully.

The impact velocity creates a strain in the input bar which is dependent on the wave velocity. With known impact velocity and known wave speed in the input bar, the strain is measured at gage position while the specimen and output bar are not in place. By varying the impact velocity, the linearity of the system can be checked and the strain gage can be calibrated.

Dynamic calibration of the system is made by sending a known pulse through the pressure bars with the specimen removed and the pressure bars joined. Knowing the impact velocity, the strain signals are recorded in both pressure bars simultaneously. These can be displayed on the oscilloscope as two separate traces; the length of one trace is directly proportional to the maximum strain of the transmitted pulse, and the length of the other trace is directly proportional to the integral of the incident strain pulse. Once the linearity of the system is established, the incident pulse has a fixed rate. Therefore, a single calibration shot serves to calibrate the scope deviation in terms of actual strain in the pressure bars independent of various systems parameters (gage factor, amplifier gains, excitation voltage) since these parameters do not change during the testing.

Calibration of the system in axial inertia is done without the specimen. If the rate of strain (which is measured from the reflection wave) is constant, then the inertial effect vanishes.

Because the specimen yields during the test, its cross-sectional area does not remain constant. Furthermore, the material work hardens as deformation proceeds. Since the reflection strain depends on the specimen material and it is the driving factor of strain rate, the strain rate generally decreases during the test.

SECTION VI

APPLICATION

For years materials have been subjected to dynamic tests to find stress-strain behavior. Various dynamic procedures and methods are available in research and industry. These procedures and methods are classified in terms of the strain rate induced in a specimen. The Hopkinson pressure bar test method is capable of measuring stress-strain behavior under a strain rate of 50/sec. to 10^4/sec. As mentioned in Section V, the test apparatus depends on the material under consideration, while the material constitutive relationship is assumed to be linear elastic.

The split Hopkinson pressure bar test apparatus has been used extensively for compression and to some extent, tension testing of metals. Since metals are considered isotropic and homogenous, the Hopkinson pressure bar test is a versatile tool to measure the mechanical behavior. Composite materials are not isotropic, have lower stiffness than the metals, and have lower wave velocity. Lower wave velocity will increase the equilibrium transit time in the specimen which requires longer pressure bars. The design of the test setup, which was presented in Section V, has assumed a lower bound wave velocity as a design variable for the material under consideration. Thus, the presented Hopkinson pressure bar test apparatus is capable of measuring stress-strain relationships for composite and/or conventional materials with wave velocity higher than 103,000 inch/sec. (7948 m/sec.). Most composite materials, as well as conventional materials, have a higher wave velocity value which makes this proposed test apparatus versatile, being applicable with materials having a wide range of wave velocity. A direct relationship exists between the length of the specimen and wave velocity which determine the length of bars. The equilibrium transit time in the specimen increases when the length of the specimen increases. Therefore the length of the specimen should be shorter for materials with lower wave velocities to compensate for the wave velocity effect on the bar length. The wave velocity of composite material should be verified using ultrasonic stiffness measurement.

In the compression test, the length of the specimen should not be more than the diameter of the bars due to the friction and inertia effect as well as local or global buckling. Therefore, the length of the specimen is limited by the diameter of the bar. Kolsky studied the frictional effect at the specimen-bar interface (Reference 6). He used an energy approach which considered the non-uniformity of the stress level in the specimen, including the effect of stress rate variation. He concluded that the desired specimen length in terms of Possion's ratio and diameter of the cylindrical specimen is $L = \sqrt{3\nu}\, d$.

If the Possion's ratio is known for the composite material, the length of specimen is uniquely defined. Since the Possion's ratio of carbon-carbon composite is not known at the present time, the specimen length should be adjusted to eliminate the frictional resistance of specimen and bars. Also, the variation of strain rate will be examined for inertia effects via the reflected wave in input bar.

In order to ensure full contact without any slip between the specimen holder and cylindrical dog bone specimen in the tension test setup, there should be a pre-tension stress at the interface. The magnitude of such a pretension should be based on the composite material and its machining tolerances. In practice this means that a series of split collars having slightly different lengths will be required to compensate for machining tolerances in the specimen. The effect of prestress on specimen properties will have to be examined. The magnitude of this stress can be measured by the strain gages on the Hopkinson bars.

The tension specimen should fail near its middle. If the failure occurs at the shoulders of the dog bone, the length of the conical shaped shoulders should be increased to distribute the contact forces, or a larger contact surface is needed. Since the specimen holder is connected to the bars by a high strength nut, manufacturing an altered dimension specimen holder does not change the remaining parts of the test setup. However, such a change may be desirable for other types of composite or conventional materials. The failure surface should be examined using a microscope to report the types of failure (brittle failure, brittle failure with fiber pullout, brittle failure with debonding and/or matrix failure).

A minimum of two specimens (longitudinal and transverse) for each type of testing is required to measure the stress-strain behavior. In general, at least three specimens (one cut along each of the principal material axes) are required to measure the strength along the principal material direction. However, for this research a transverse symmetry exists in the supplied carbon-carbon composite material.

The specimen should be without any flaw or damage; therefore, the composite material should be examined for cracks, flaws, and imperfections before machining. A X-ray system can be utilized to locate the flaws in conjunction with a C-Scan Ultrasonic inspection system for interrogation of damaged and opaque structural composite.

A. ANALYSIS OF MEASUREMENTS

In order to determine the stress-strain relationship of composite material at high strain rate, the velocity of impact bar has to be controlled. If the stress wave is below the yield point of pressure bars and the bars are assumed to be linear elastic, the transmitted strain in the output bar can be expressed in terms of strain rate. There are three direct measurements in the Hopkinson pressure bar test apparatus regardless of loading type:

1. The velocity of striker bar upon impact.

2. Strain measurements in the input or incident pressure bar.

3. Strain measurement in the output or transmitted pressure bar.

As was mentioned in the instrumentation section of Section III, the velocity of striker bar is measured by a time counter. The intensity of the stress wave is directly dependent upon the velocity of the striker bar upon impact:

$$\sigma = \rho \, CV/2 \tag{49}$$

This stress creates a strain in the input bar and can be measured as the wave travels toward the specimen. The rise time of the stress wave depends on the perfection of alignment between the impact face of striker bar and the input bar. With reasonable alignment, a rise time of 2-3 microsecond is possible. The compressive wave will reflect back from interface of the bar and specimen and pass through the strain gage where the strain will be recorded on an oscilloscope. It is important to note that the reflected strain increases due to the number of internal reflection in the specimen. The transmitted wave propagates into the output bar and is measured by the strain gage mounted on output bar.

Knowing the incident, reflection, and transmitted strain, the strain in the specimen can be calculated. Equation 27 gives the average strain in specimen interior as a result of the reflected strain as:

$$\epsilon_s = - \frac{2C}{L} \int_0^t \epsilon_r \, dt \tag{50}$$

The wave velocity (C) and length of the specimen are known; therefore, the strain can be integrated using Simpson's rule as:

$$\epsilon_s = \frac{-2C\,\Delta t}{3L}\,(\epsilon_r^{o} + 4\epsilon_r^{1} + 2\epsilon_r^{2} + 4\epsilon_r^{3} + \cdots + 2\epsilon_r^{n-2} + 4\epsilon_r^{n-1} + \epsilon_r^{n}) \quad (51)$$

Where $\Delta t = \frac{t}{n}$

Knowing the transmitted strain, the corresponding stress can be calculated using Equation 28; consequently, the stress and strain at a point is calculated and can be presented by a stress curve using a computer. The average strain rate corresponding to such a curve is calculated by Equation 29. Since the reflected and transmitted stain is not constant with respect to time, the strain rate may not be constant. As strain increases the strain rate may change but the average strain rate can be calculate.

B. LIMITATION OF THE TESTER

The test equipment described in Section V permits the determination of the stress and strain rate relation of many materials in the wide range of strain rates. However, there are certain limitations inherent in the method and design.

(1) The equilibrium transit time should be greater than the total duration of the test. Therefore, the wave velocity of specimen should be large enough to reach equilibrium before the test is finished. In addition, the equilibrium transit time should be less than the duration of the secondary stress wave generated by reflection in the striker bar. The data obtained at very low strain values may not be reliable because the equilibrium in specimen is not established.

(2) The Hopkinson pressure bar assumes linear elastic behavior for pressure bars. Therefore, the stress level should not exceed the yield strength of pressure bars. If plastic deformation takes place in pressure bars (mostly in the input bar), the analysis as described in Section V no longer applies. Since the strain rate is controlled by the magnitude of initial stress wave, the strain rate generated in the specimen will be limited.

(3) The stress, stain, and strain rate in specimen are assumed to be uniform and measured as average values. The deviations from this condition can result from frictional boundary restraint. The specimen-pressure bar interface shear stress should be as low as possible. Proper lubrication of the interface will reduce shear stress so that the radial deformation will be uniform in specimen (no barreling). There is evidence

that the efficiency of lubrication is greater in the high strain rate than normal or quasi-static test. The specimen should be polished in the compression and tension test setup.

(4) The strain acceleration in specimen creates axial inertia which is caused by the finite dimension of the specimen and non-uniformity of stress and strain. The strain acceleration is decreasing as the stress is accumulated in the specimen. The variation of strain acceleration is found to be very dependent upon specimen material, duration of the test and specimen length.

(5) The operation of the Hopkinson pressure bar tester and the interpolation of the recorded measurement requires a through understanding of mechanical and electrical systems involved. In addition, selection of specimen dimensions should be consistent with the theory used in this test setup.

SECTION VII

CONCLUSION

The split Hopkinson pressure bar is selected from many test procedures based on its versatility of achieving high strain rates ranging from 50 in/in/sec to 10^4 in/in/sec and its use of small specimens. An extensive study was performed on the split Hopkinson pressure bar under compression, tension, and shear test procedures and setup. The following conclusion and recommendations were drawn.

- o Compression specimen configuration and dimension is designed based on axial inertia, frictional contact of specimen and pressure bar and fiber location, concentration and spacing. The shape of the specimen is chosen to be cylindrical with the ratio of diameter to the height to be 0.5.

- o Assuming the elastic modulus, mass density of carbon-carbon composite, the equilibrium transit time is calculated to determine the length of the pressure bars.

- o Based on equilibrium transit time, the duration of impulse load is calculated and the length of the striker bar is selected.

- o The length of all pressure bars is selected based on the equilibrium transit time and duration of impulse load.

- o The pressure gas gun requirement is determined to produce enough pressure on the striker bar to maintain a constant velocity. The primary design of pressure gas gun is performed.

- o Shear specimen configuration and dimensions are designed based on the fiber bundles concentration and spacing. Failure modes play an important role in the selection of shear specimens.

- o Shear specimen holder and the position of specimen is designed for interlaminar and transverse shear test setup.

- o A dog bone tension specimen is selected to ensure the location of the failure (in the middle of the specimen).

- o Tension specimen holder is designed to produce direct tension in the dog bone specimen and to prevent any off-axis loading.
- o Mode of failure was studied in all types of test setup. The specimen configuration was selected based on desired mode of failure.
- o The stress distribution in the pressure bars was studied with respect to the velocity of the striker bar and stress concentration.
- o The bar material selected is stainless steel. It will transmit the high stress waves to the specimen and remain linear elastic.
- o Strain gage, timer, and measurement instrumentation are selected to ensure proper reading of strains and velocity of striker bar.
- o Calculation of stress-strain behavior and applied strain rates are presented from incident, reflected and transmitted strain measurement.

Every effort has been made in this study to provide basic details about the Hopkinson pressure bar testing system for compression, tensile, and shear testing of composite material. There remain a number of subtle and important considerations that are the subject matter of further investigation (Phase II). These considerations can best be accounted for by building these testing devices and carrying out the actual tests under different loading conditions on the carbon-carbon composite systems under question. The following questions and considerations should be investigated and addressed in a Phase II program.

- o Poisson's ratio variation of the composite and its effect on the compression testing.
- o Determination of wave velocities in the composite along the principal axes using a non-destructive evaluation technique.
- o Design refinements (tolerance, fit, and matching) in tension specimen holder.
- o Effects of variations in specimen size in tension, compression, and shear testing.
- o Effect of a small amount of pretension in the specimen on the response of a tension specimen.

- Determination of equilibrium transit time through a specimen.
- Fabrication and testing of a gas gun launching mechanism.
- Fabrication and installation of Hopkinson pressure bar systems.
- Calibration of instruments and test setup using a material (monolithic) with a known strain-rate behavior.
- Testing the given composite material for various strengths and stress-strain responses.
- Studying the effects of various failure modes on stress-strain responses and strengths for compressive, tensile, and shear loadings.

REFERENCES

1. Ross, C.A., Cook, W.H., and Wilson, L.L., "Dynamic Tensile Tests of Composite Materials Using a Split Hopkinson Pressure Bar," Experimental Techniques, Nov. 1984.

2. Zukes, J.A., Nicholas, T., Swift, H.F., Greszezuk, L.B., and Curran, D.R., Impact Dynamics, John Wiley and Sons, N.Y., 1982.

3. Holzer, A.J., Int. Journal of Mech. Sci., 20, 553, 1978.

4. Holzer, A.J., and Brown, R.H., Journal Eng. Mat. Tech. Trans. ASME 101, 238, 1979.

5. __________, "Impact Testing of Metals," ASTM Special Publication, 1970.

6. Kolsky, H., "An Investigation of Mechanical Properties of Materials at Very High Rates of Loading," Proceedings of the Physical Society, Section B, Vol. 62, 1949.

7. Lindholm, U.S., "Some Experiments with the Split Hopkinson Pressure Bar," Journal of Mech. Physics of Solids, Vol. 12, 1964.

8. Davies, E.D.H., and Hunter, S.C., "The Dynamic Compression Testing of Solids by the Method of the Split Hopkinson Pressure Bar," Journal of Mech. Physics of Solids, Vol. 11, 1963.

9. Maiden, C.J., and Green, S.C., "Compressive Strain Rate Tests on Six Selected Materials at Strain Rates from 10^{-3} to 10^{4} in/in/sec.," ASME Transactions, Vol. 33, 1966.

10. Hauser, F.E., "Techniques for Measuring Stress-Strain Relations at High Strain Rates," Experimental Mechanics, August 1966.

11. Nicholas, T., "Tensile Testing of Materials at High Strain Rates," Experimental Mechanics, May 1981.

12. Ohlson, N.G., "Determination of Crack Initiation at High Strain Rates," Journal of the Institute of Physics, 47, 1979.

13. Harding, J., "The High-Speed Punching of Woven-Roving Glass-Reinforced Composites," Journal of the Institute of Physics, 47, 1979.

14. Klepaczko, J., "Application of the Split Hopkinson Bar to Fracture Dynamics," Journal of the Institute of Physics, 47, 1979.

15. Werner, S.M., and Dharan, C.K.H., "The Dynamic Response of Graphite Fiber-Epoxy Laminates at High Shear Strain Rates," Journal of Composite Materials, 4, 1986.

16. Ruiz, C., and Mines, R.A.W., "The Hopkinson Pressure Bar: An Alternative to the Instrumented Pendulum for Charpy Tests," International Journal of Fracture, 29, 1985.

17. Lindholm, U.S., and Yeakley, L.M., "High Strain-Rate Testing: Tension and Compression," Experimental Mechanics, Vol. 8, 1968.

18. Davies, C.K.L., Turner, S., and Williamson, K.H., "Fluxed Plate Impact Testing of Carbon Fiber-Reinforced Polymer Composites," Composites, Vol. 16, No. 4, Oct. 1985.

19. Brontman, L.J., and Rotem, A., "Impact Strength and Toughness of Fiber Composite Materials," Presented at ASTM Symposium on Foreign Object Impact Behavior of Composites, September, 1973.